Sponsored by RF & Optical Systems, Systems Design, and The Ed Wells Initiative

Commercial Satellite Communication Applications

Course No. 9SV109

Student Guide
Volume II

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The Textbook & Student Guides for this course are provided to qualified attending employees compliments of...

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References

Reference 1	A Structured Overview of Digital Communications "A Tutorial Review"
Reference 2	Guide for Metric Practice
Reference 3	Telecommunications for the 21st Century
Reference 4	The Orbiting Internet "Fiber in the Sky"
Reference 5a	Engineering Issues & Design Choices (Comparison - TDMA, FDMA)
Reference 5b	Engineering Issues & Design Choices (Comparison - TDMA, FDM, CDMA)
Reference 5c	Physics of Satellite Communications (RF Basics - Frequency Spectrum)
Reference 5d	Physics of Satellite Communications (RF Basics - Frequency Bands)
Reference 6	Chart - Commercial Supercomputer Products
Reference 7	Defense Department Constructs Global Communications Network
Reference 8	Symbols and Acronyms

Course Agenda

Day 1

Introduction

Module 1 - Overview of Boeing Commercial Satellite Projects

Module 2 - Satellite Technology

Lunch

Module 3 - Satellite Links and Access Methods

Module 4 - Frequency Coordination and Regulation

Day 2

Module 5 - Direct-to-Home Television Services

Module 6 - Telephone Services

Lunch

Module 7 - Data/Multimedia Services

Module 8 - Systems Descriptions of Boeing Commercial Satellite Projects

Course Evaluation

Day 1 Agenda

8:00	**Introduction**
8:10	**Module 1: Overview of Boeing Commercial Satellite Projects**
9:00	**Module 2: Satellite Technology**
	Module 2A: Orbits
9:30	**Module 2B: Bus Subsystems**
10:00	*Break*
10:15	**Module 2C: Communication Subsystem**
11:00	**Module 2D: Tracking, Telemetry, and Command**
11:30	*Lunch*
12:15	**Module 3: Communications 101**
2:30	*Break*
2:45	**Module 4: Frequency Coordination and Regulations**
4:30	*End of Day*

Day 2 Agenda

8:00	**Module 5: Direct-to-Home Television Services by Satellite**
9:45	*Break*
10:00	**Module 6: Telephone Service**
11:15	**Module 7: Data/Multimedia Services**
11:45	*Lunch*
12:30	**Module 7: Data/Multimedia Services (cont)**
1:15	**Module 8: Boeing Commercial Satellite Projects--System Descriptions**
	Module 8A: Teledesic
2:00	**Module 8B: Global Broadcast Service**
2:30	**Module 8C: Resource 21**
3:00	*Break*
3:15	**Module 8D: DigitalXpress**
3:45	**Module 8E: Aviation Information Services**
4:15	**Course Evaluation**
4:30	*End of Day*

Web Page - Course Description

http://plato.ds.boeing.com/training/CSatDesc.htm

This course provides a broad overview of how satellites are used to provide communications; it is intended for both engineers and managers with a wide range of experience levels. Students learn terminology & technology of satellite communications, including:

1) communication satellite system architectures,
2) satellite constellations,
3) communication satellite payloads and other subsystems,
4) the regulatory environment/ governmental license process and allocation of frequency bands around the world,
5) direct broadcast satellite (DBS) service and technologies, and
6) satellite links and access methods.

The technical discussion includes applications for specific products and services. The course includes a review of the major satellite communications projects within Boeing Information, Space, & Defense Systems.

Course Objectives

Upon completion, students should be able to:

- **Describe satellite communications fundamentals to the growing number of employees working on projects related to satellite communications.**
- **Explain the differences between communications satellite system architectures, satellite constellations, satellite bus and payload designs, and multiple access and modulation techniques.**
- **Explain the regulatory process and applications of satellite communications**

Course Development & Review Team

http://plato.ds.boeing.com/training/CSatTm.htm

Bob Higgins
Bill Richards
Jeff Krinsky

Steve Cuspard
Ed Gentzler
Bill Milne
Bob Perovich
Jim McClelland

1st Instructor Introduction

http://plato.ds.boeing.com/CSatTms.htm

Bill Richards 3E-80 253 / 773-8849

william.r.richards@boeing.com

Background / Qualifications for teaching course:

- **Senior Principal Engineer, DigitalXpress & Aviation Information Services Systems Team**
- **Systems Engineer Manager Ku-band Systems, Hughes Communciations Incorporated**
- **10 years Systems Engineering on commercial communications satellites at Hughes**

2nd Instructor Introduction

http://plato.ds.boeing.com/CSatTms.htm

Bob Higgins 8H-12 253 / 773-3250

robert.p.higgins@boeing.com

Background / Qualifications for teaching course:

- Senior Principal Engineer, worked early on Teledesic, currently working on AIS
- Communication system design for LPI Radio
- Initial SATCOM work on R-21
- Initial Phase III concept work on GBS

Additional Resources

COURSES:

- Course #9SV608 “Satellite Communications” (Off-Hr.), 30 hrs. For course description, see-- http://natasha.ca.boeing.com/courses/0/8/9SV608.html
- Course #9SV1001 “Coding Theory” (Off-Hr.), 30 hrs. For course description, see-- http://natasha.ca.boeing.com/courses/0/1/9SV1001.html
- George Washington University continuing engineering education courses in satellite communication. http://www.gwu.edu/~ceep/g-documents/comm2.htm
- Applied Technology Institute courses on satellites and communications. http://catalog.com/hitekweb

Additional Resources

- **UCLA Extension courses.**
  http://www.ucla.edu/home/continuing.html

BOOKS: Communications

- **Morgan and Gordon, *Communications Satellite Handbook*, Wiley, 1989**
- **Bernard Sklar, *Digital Communications, Fundamentals and Applications*, Prentice Hall, 1988**
- **John G. Proakis, *Digital Communications*, 2nd edition McGraw-Hill, 1983**
- **J.C. Bic, et.al., *Elements of Digital Communications*, Wiley, 1991**

Additional Resources

- Roger Freeman, *Reference Manual for Telecommunications Engineering*, Wiley, 1985

Coding Theory

- Michelson and Levesque, *Error-Control Techniques for Digital Communications*, Wiley, 1985
- Lin and Costello, *Error Control Coding: Fundamentals and Applications*, Prentice-Hall, 1983
- Peterson, Weldon, *Error-Correcting Codes*, MIT Press, 1972

Antennas

- Constantine Balanis, *Antenna Theory, Analysis and Design*, Wiley, 1982

Additional Resources

Computer Networks

- Andrew Tanenbaum, *Computer Networks*, Prentice-Hall,

Data Compression

- Jayant & Noll, *Digital Coding of Waveforms, Principles and Applications to Speech and Video*, Prentice-Hall, 1984
- Bhaskaran & Konstantinides, *Image & Video Compression Standards, Algorithms and Architectures*, 2nd edition, Kluwer Academic, 1997

Propagation

- Brussaard and Watson, *Atmospheric Modeling and Millimetre Wave Propagation*, Chapman and Hall,

Additional Resources

- Warren Flock, *Propagation Effects on Satellite Systems at Frequencies Below 10 GHz*, NASA Reference Publication 1108 (02), 1987

Space Systems

- TRW Space Data, TRW
- Larson & Wertz, *Space Mission Analysis and Design*, Kluwer Academic, 1992
- Bate, Mueller, & White, *Fundamentals of Astrodynamics*
- Piscane & Moore, *Fundamentals of Space Systems*, 1994

Sign the Roster

Record your attendance on the roster:

- **Initial the roster (to the left of your name)**
- **Record the # of hours you will attend today:**

  > ***If you will attend ALL of today's class,***
  > ***put "8" (for 8 hrs.) in today's box, at far right.***
  > **(1st box is for 1st day; 2nd box is for 2nd day)**

  > ***If you will attend only PART of today's class,***
  > ***record the actual number of hours you attend***
  > ***(in today's box, at far right).***

Complete a Course Evaluation

Answer these 4 questions on back of form:

12. What *did you get* from the course *that was good*?

13. What *didn't you get that you expected* from the course?

14. What would you *like to have in-hand* when you leave?

15. What *changes/improvements* would you like to see?

Hand in your Evaluation as you leave.

Ergonomics for the Computer User

Leader's Guide

GL-HS-0108

Commercial Satellite Communication Applications
Course No. 9SV109

Module 1

Overview of Boeing Commercial Satellite Projects

Module Agenda

Topic	Duration	Speaker
Teledesic	10 Min	Higgins
Global Broadcast Service	10 Min	Higgins
Resource 21	10 Min	Higgins
DigitalXpress	10 Min	Richards
Aviation Information Services	10 Min	Richards

1- 3 Module Objectives / Assessments

What you can learn in this module:

- Overview of Boeing projects relating to satellite communications

How to measure your success:

- Can you describe the major differences between the various Boeing projects?

Teledesic
Overview

- **Principle investors of Teledesic:**
  - **Teledesic (Craig McCaw)**
  - **Bill Gates**
  - **AT&T**
  - **Boeing**
- **Constellation of 288 LEO satellite to provide high rate data to users with fiber-like quality of service and delay**

Teledesic

Business/Product Description

Market - "Broadband information services to people in rural and remote parts of the U.S. and world" (fixed satellite service, FSS)

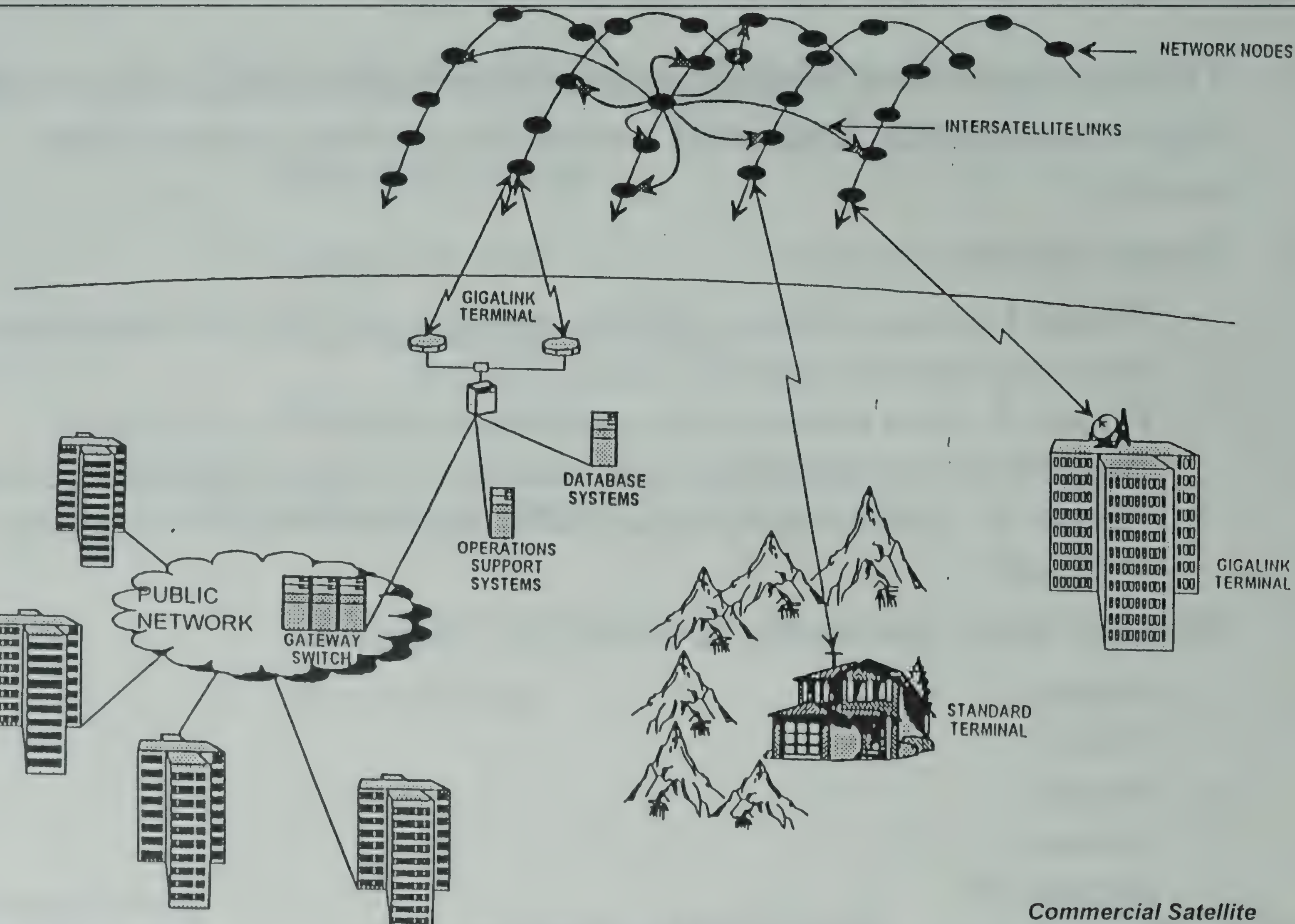
Capacity - > 20,000 T1 connections worldwide

Services

- Shared networking with an ability to multiplex and prioritize traffic from many sources
- High priority bandwidth with the characteristics of fixed circuits
- Global backbones of up to gigabit performance
- Virtual private networks (VPNs) confined to specific customers

Teledesic

1- 6 System Architecture



Global Broadcast Service (GBS)

Overview

1- 7

- DOD project leveraging commercial technology to provide high-bandwidth, low-cost communications around the world
- Three phase project
  - Phase I - Use existing satellite assets and COTS transmitters and receivers to provide data services
  - Phase II - Use asecondary payload on UFO-8, -9, -10 and ruggedized transmitters and receivers to provide data services
  - Phase III - Define and launch GBS satellites to provide data services
- Boeing team currently bidding on Phase II
  - Boeing
  - TRW
  - Harris
  - Lucent
  - Microsoft
  - Pacific Sierra Research (PSR)

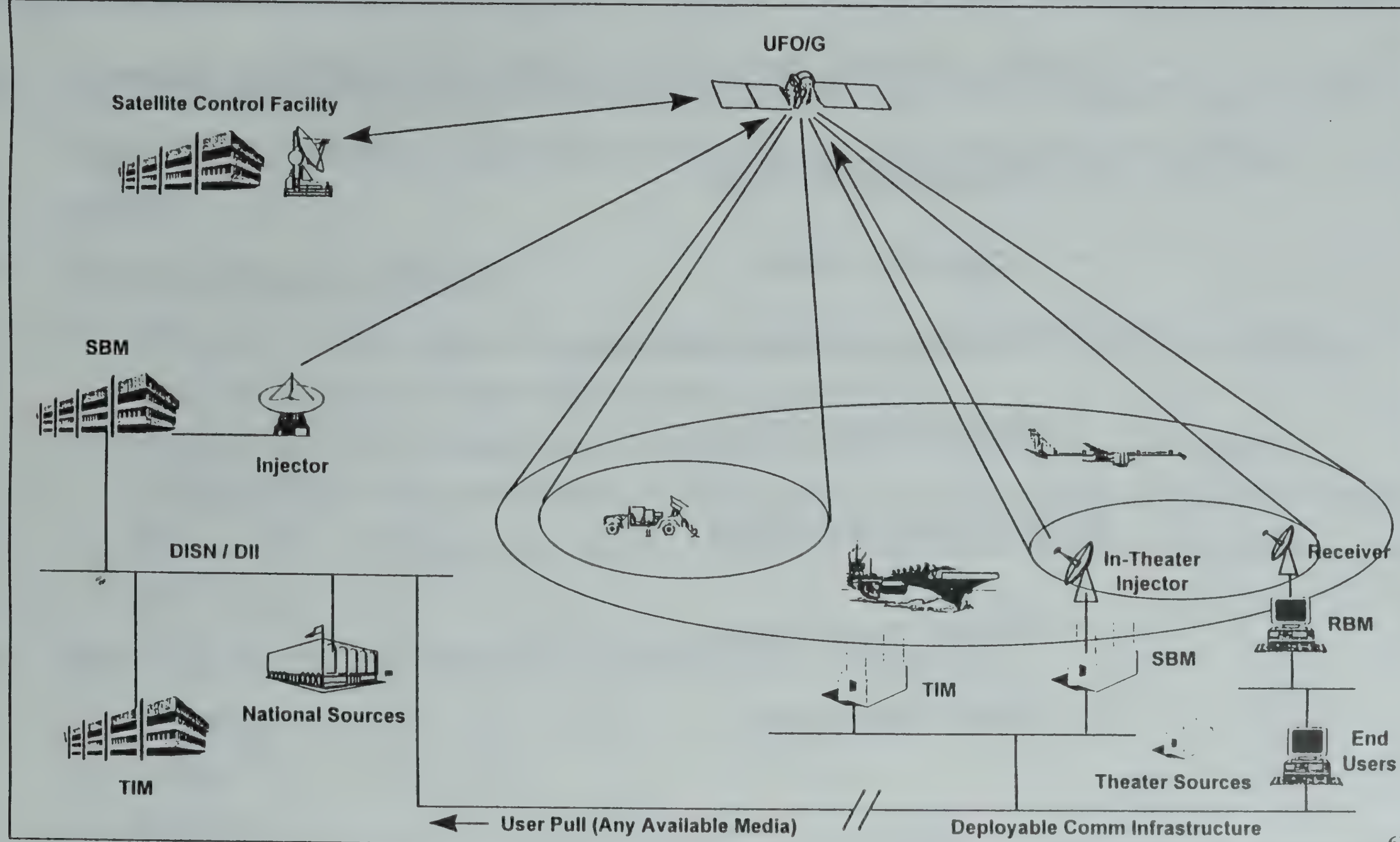
Global Broadcast Service (GBS)

1- 8 Business/Product Description

- **High volume data and video for military users**
  - **Operational data**
  - **Logistics data**
  - **Training video and data**
  - **Entertainment ?**
- **Broadcast system**
  - **Smart push data**
  - **User pull data**

Global Broadcast Service (GBS)

1- 9 System Architecture



Resource 21
Overview

Earth resources sensing satellite system

- **Multi-spectral imaging system**
- **10 meter resolution**

Partners of Resource 21:

- **Boeing Commercial Space Company (BCSC)**
-
-

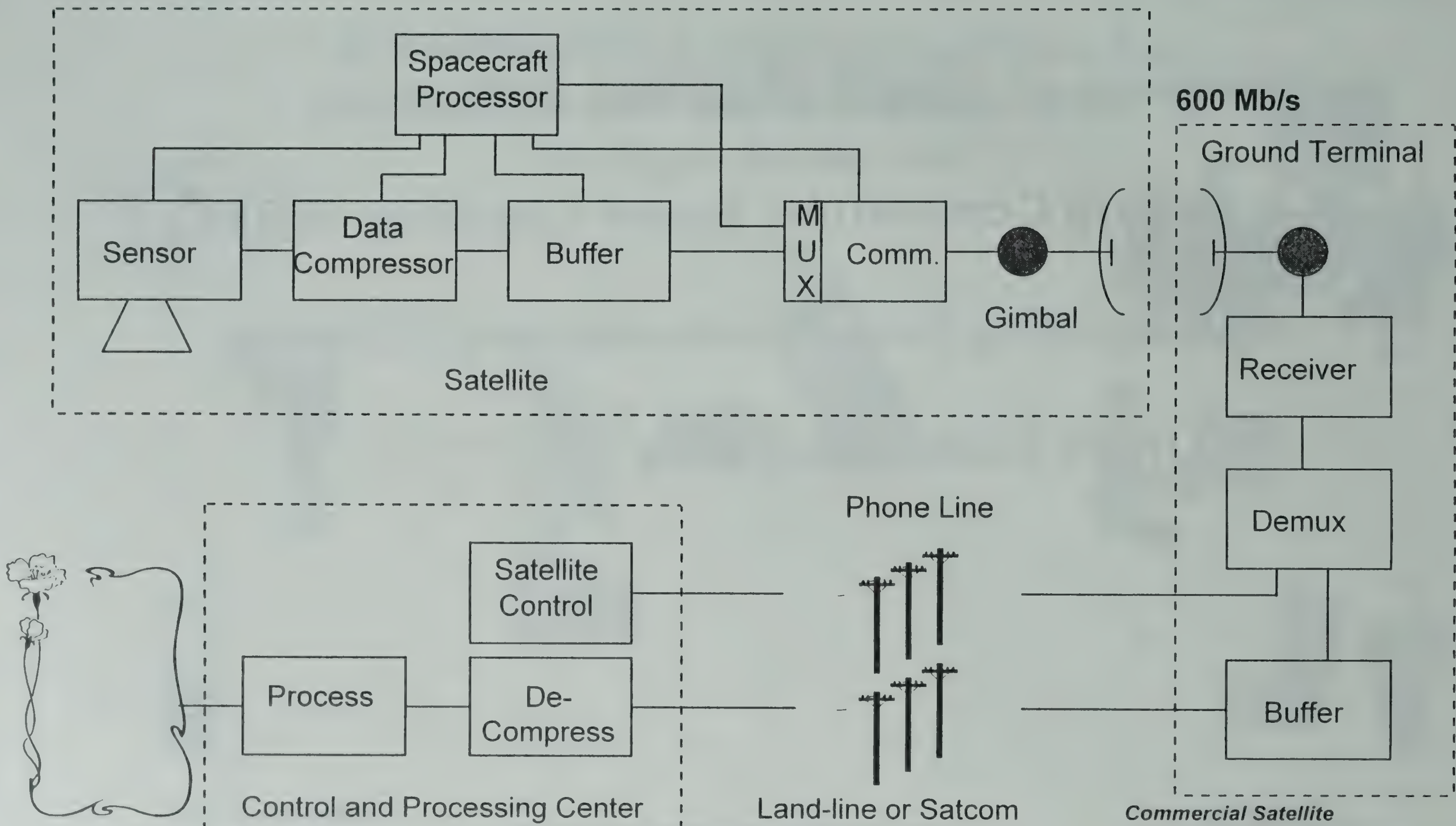
Resource 21

Business/Product Description

- **Product**
  - **Multi-spectral images**
  - **Processed images**
    - **Enables farmers to pin-point growing problems early**
    - **Enables localized application of fertilizers, pesticides, etc.**
    - **Enables prediction of crop yields**
- **Customers**
  - **Farmers**
  - **Government**
  - **Others**

Resource-21

System Architecture



DigitalXpress
Overview

1- 13

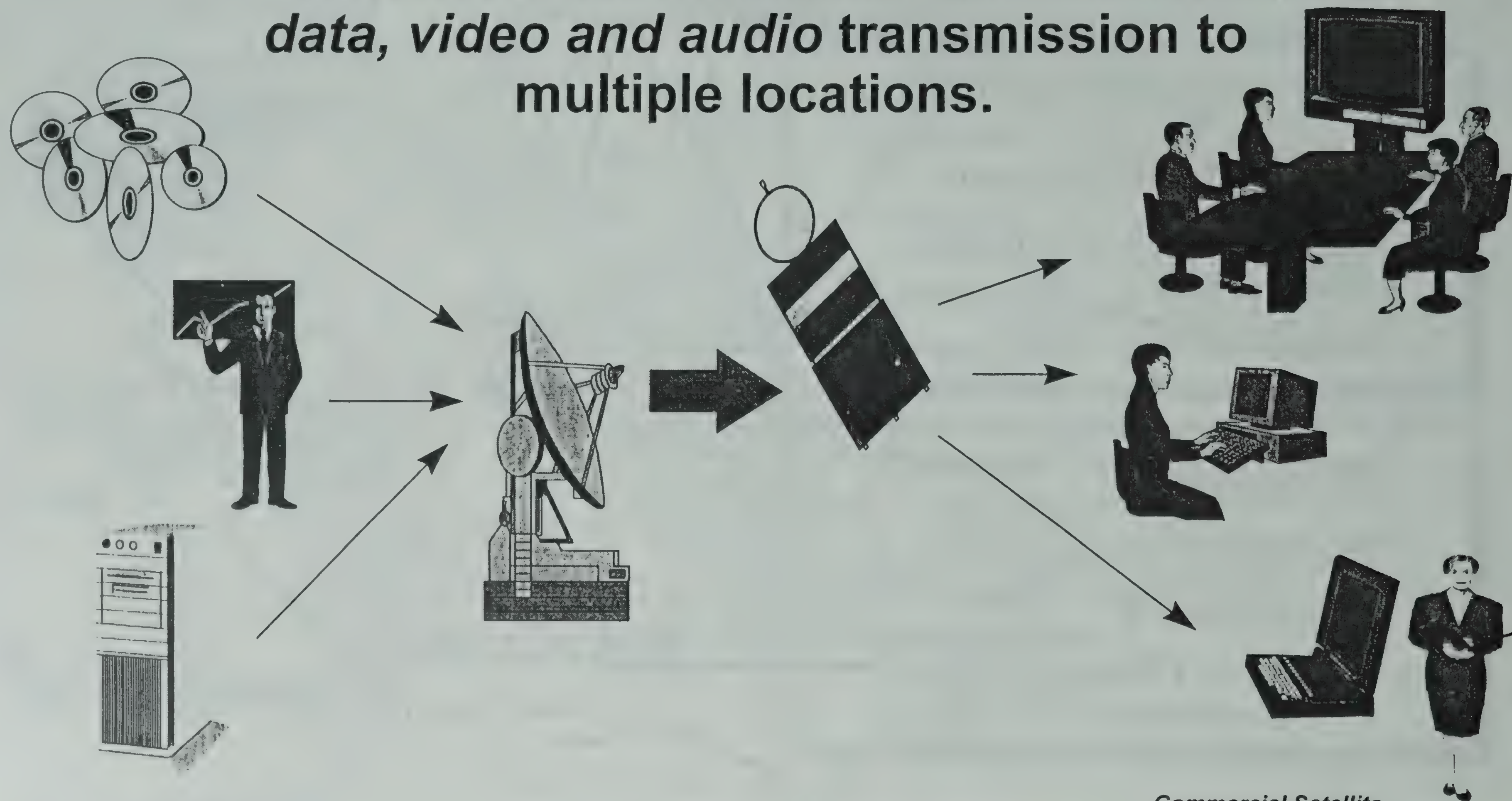
- Members of DigitalXpress include:
  - Boeing Commercial Space Company (BCSC)
  - Computing Devices International (CDI)
  - CONUS Communications

DigitalXpress

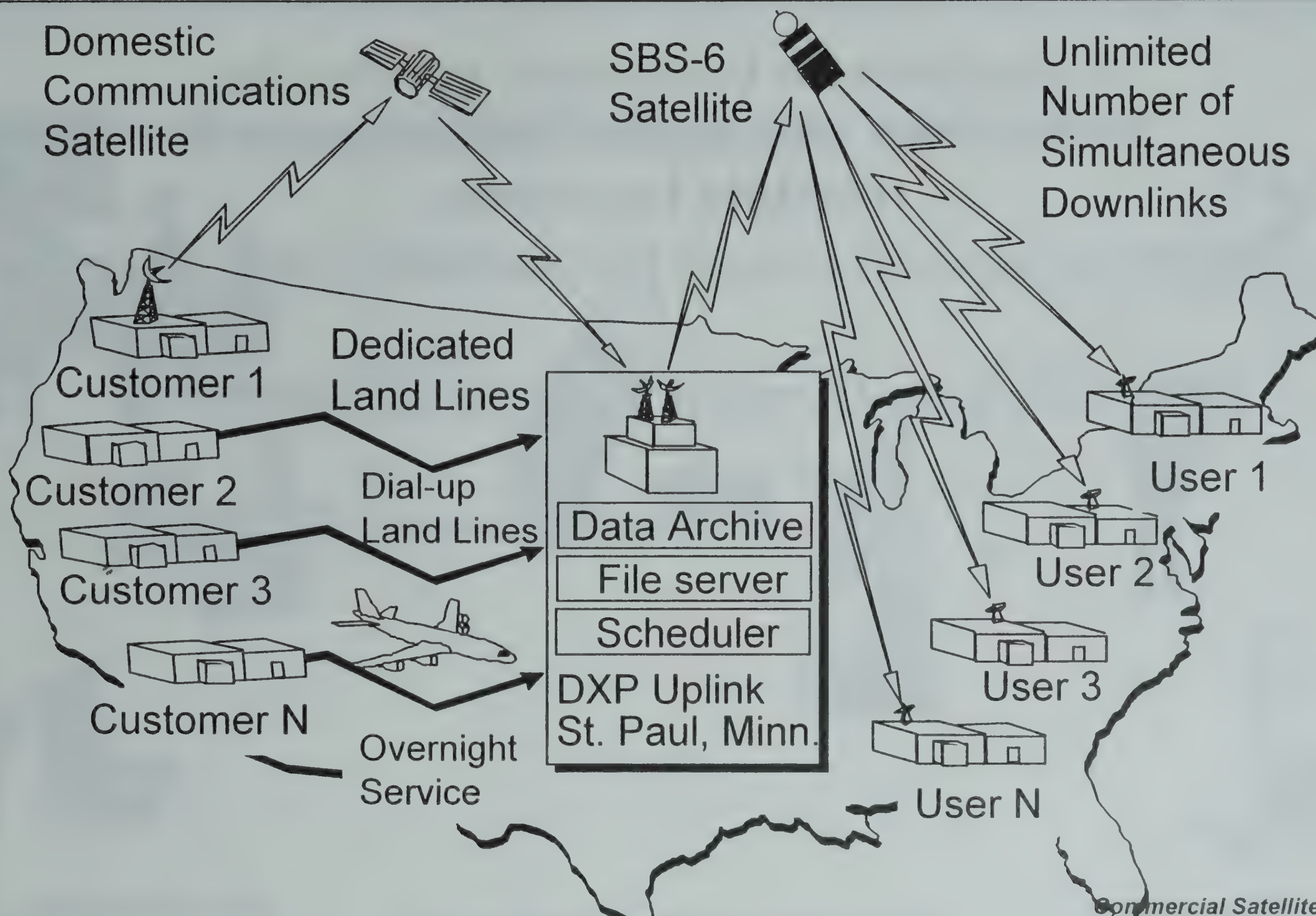
Business/Product Description

1- 14

A multimedia broadcast service for *data, video and audio* transmission to multiple locations.



DigitalXpress
System Architecture



Aviation Information Services

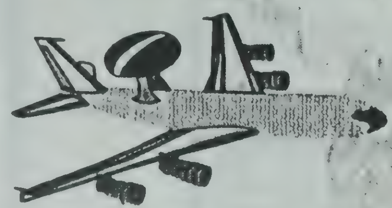
Overview

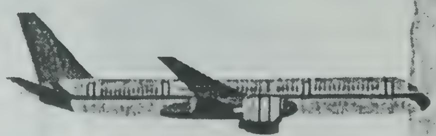
1- 16

Provide Worldwide Information Services for People on Airplanes

Value To People

- **Expanded information choices**
  - Broadcast TV (news, sports)
  - Off-board data retrieval
  - Connecting flights
- **Home/Office Environment**





Value To Customers

- **Improved fleet operations**
  - Asset management
  - Reduced operating costs
- **Enhanced passenger satisfaction**
- **Expand support to our traditional customers**

Aviation Information Services

Business/Product Description

Flight Crew
- Flight plans/ checklists
- Aircraft operations manuals
- Navigation charts
- Minimum equipment list
- Performance calculations
- Logbooks

Cabin Crew
- Cabin logs
- Passenger manifest
- Connecting gate information
- Departure reports

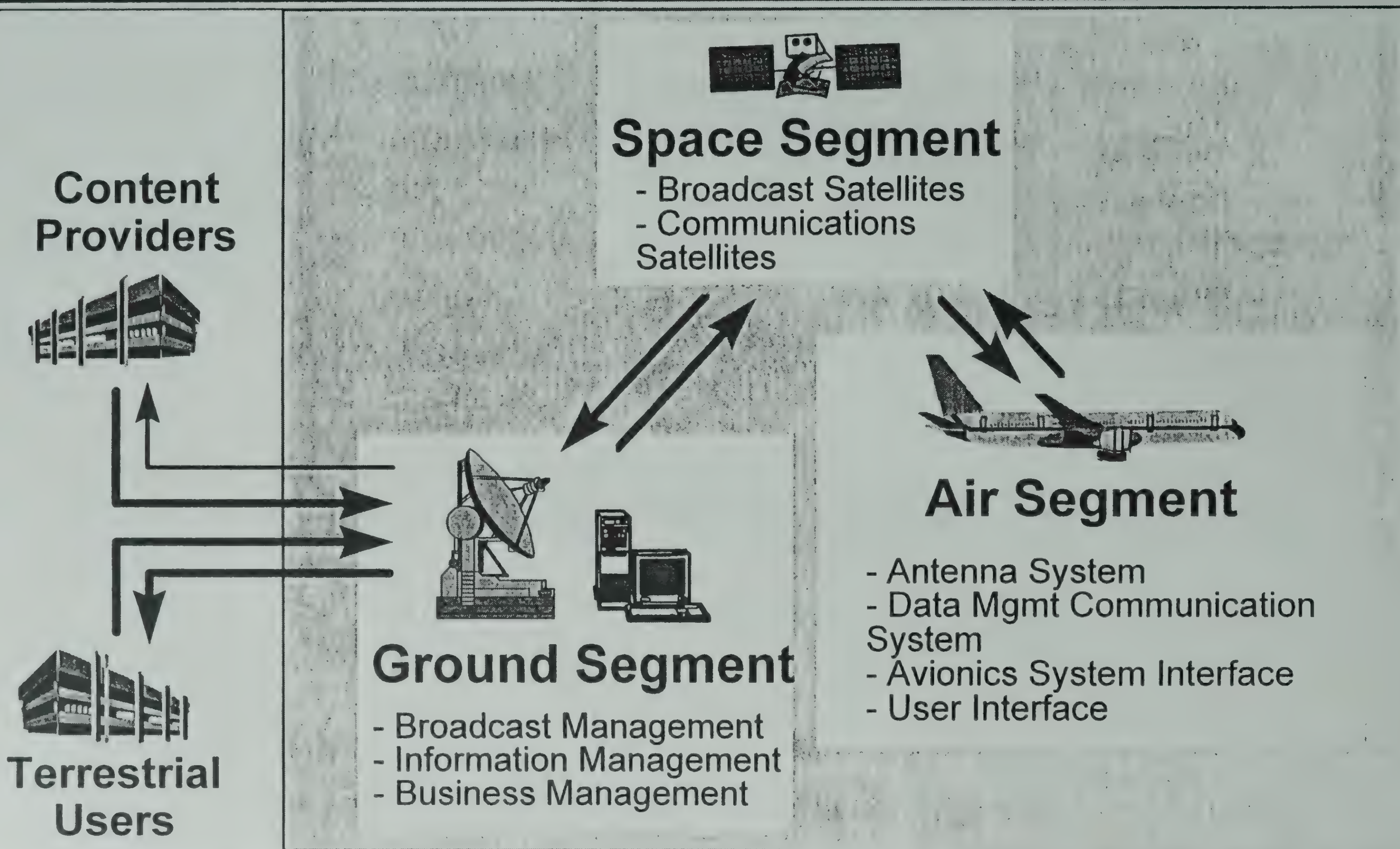
Passenger Information/ Entertainment
- Broadcast TV
- Movies/ entertainment
- Business Information
- Weather
- Currency/ Customs
- Destination guides

Maintenance Crew
- Fault isolation manual
- Maintenance manuals
- Illustrated parts catalog
- System schematics

Aviation Information Services

System Architecture

1- 18



Notes

1- 19

Commercial Satellite Communication Applications
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Module 8

Boeing Commercial Satellite Projects System Descriptions

8- 2

Module Agenda

Topic	Duration	Speaker
A. Teledesic	45 Min	Higgins
B. Global Broadcast Service	30 Min	Higgins
C. Resource 21	30 Min	Higgins
D. DigitalXpress	30 Min	Richards
E. Aviation Information Services	30 Min	Richards

8- 3

Module Objectives / Assessments

What you can learn in this module:

- **How items learned in Modules 2-7 apply to current Boeing satellite communications projects**
- **How current Boeing communications projects compare to each other**

How to measure your success:

- **Can you list the major features of each communications architecture?**

Notes

8- 4

Commercial Satellite Communication Applications
Course No. 9SV109

Module 8A
Teledesic

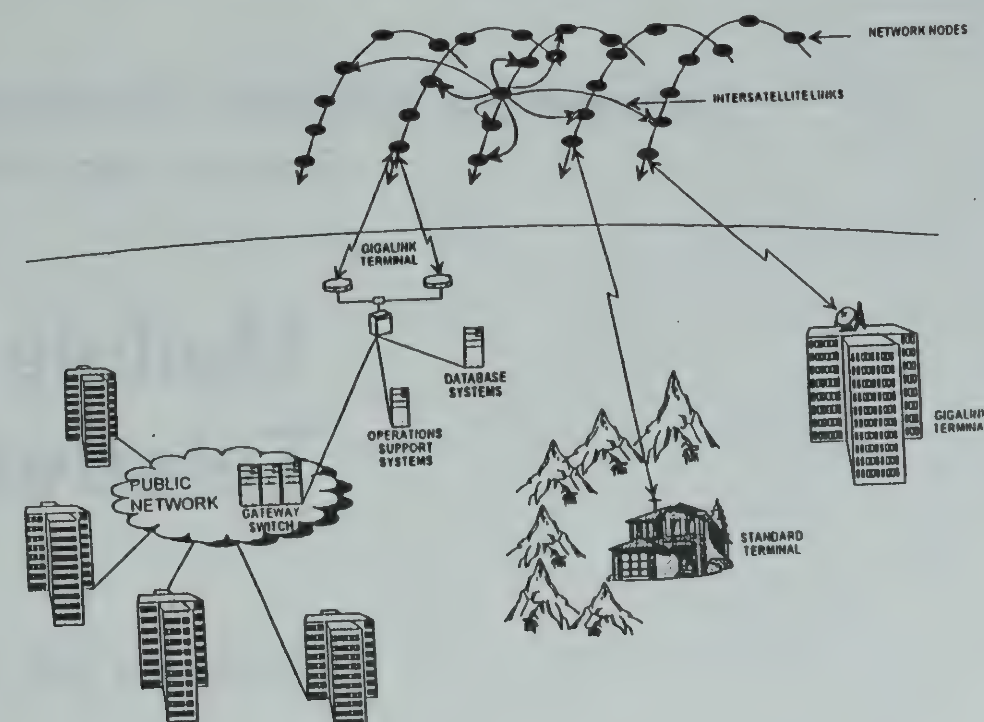
October 24, 1997

Boeing Information, Space, & Defense Systems

Teledesic Network

8A- 2

- Description based on SEP-1 proposal Nov 1996
- Market - "Broadband information services to people in rural and remote parts of the U.S. and world" (Fixed Satellite Service, FSS)
- Capacity > 20,000 T1 connections worldwide



Teledesic constellation

8A- 3

288 Satellites

- **12 planes**
- **24 satellites/plane**

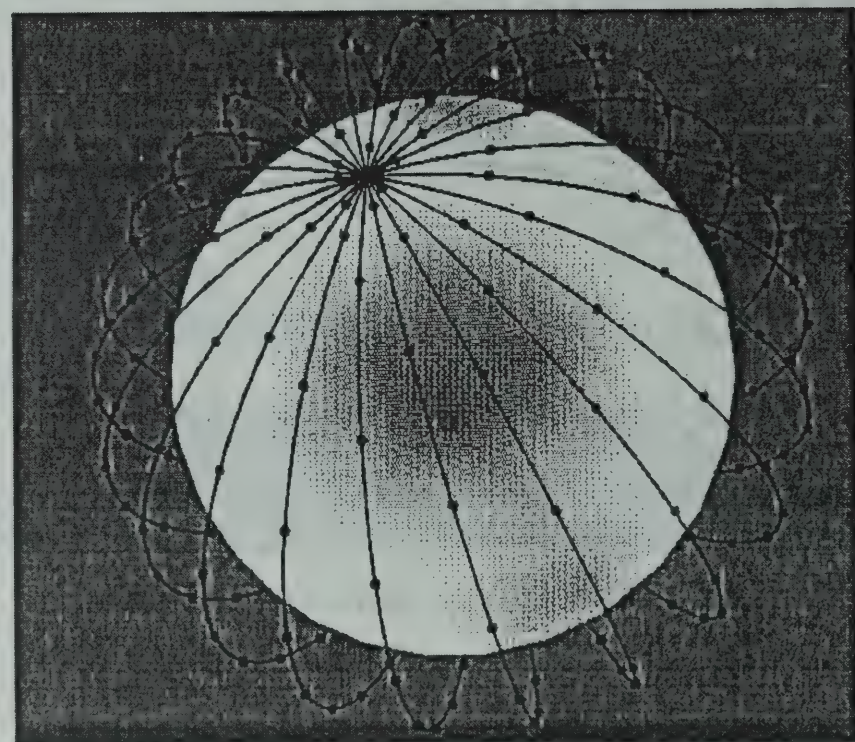
Altitude - 1350 km

Inclination - 90°

Orbit period - 1.88 hours

Visibility period

- **10° elevation - 16.1 minutes**
- **40° elevation - 6.78 Minutes**



Teledesic Satellite

8A- 4

Life - 10 years

Mass - 1338 kg fueled

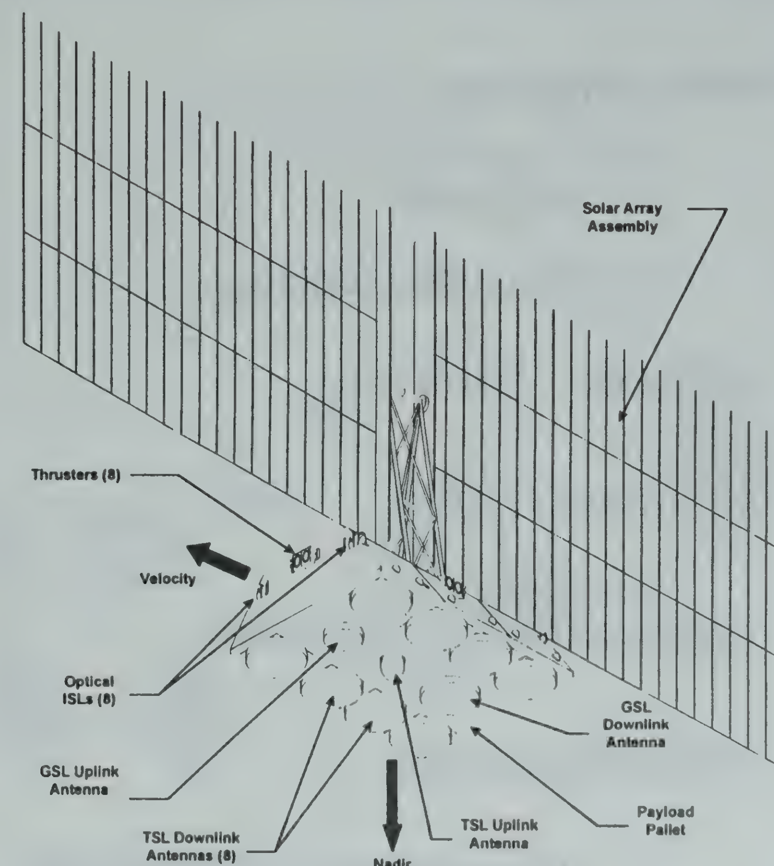
Size - 3.35 x 2.65 x 0.66 meters

Power

- 35 m^2 terrestrial solar cells
- 5400 watts beginning of life
- 10.8 kWH Lithium-ion batteries

Attitude control - 3 axis to 0.25 °

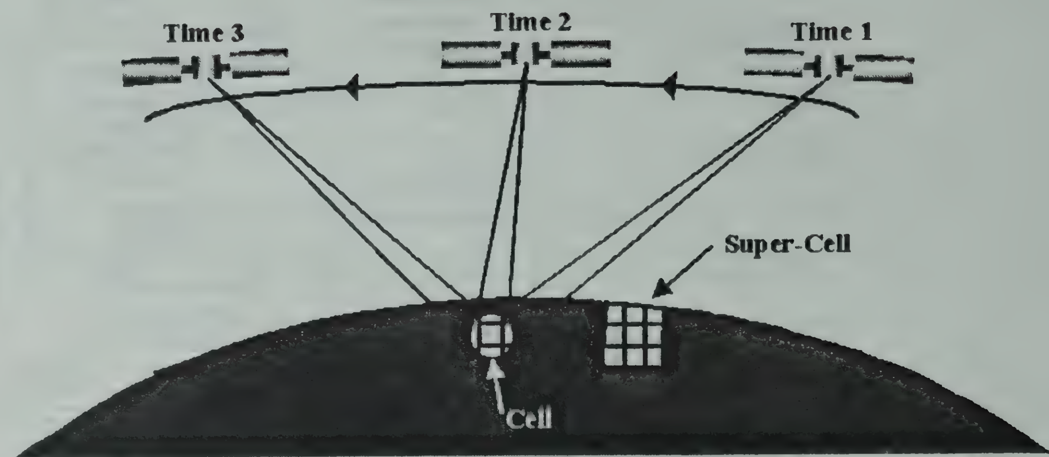
Propulsion - Xenon electric propulsion



Spot Beam Architecture

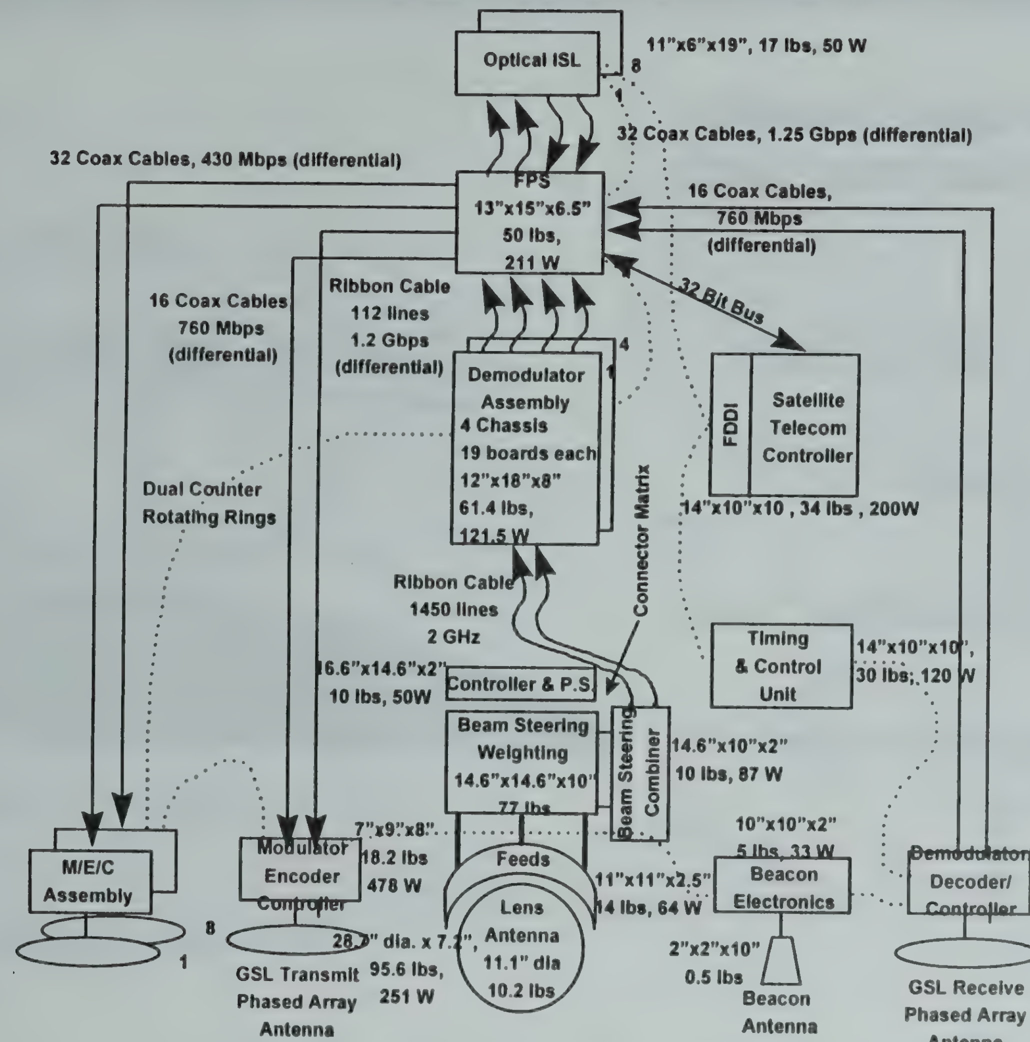
8A- 5

- Earth fixed cells (satellite antennas must track earth spot)
- Hexagonal spot pattern
- 80 km spot size
- 725 spots in satellite field
- 7-cell frequency reuse



Payload Block Diagram

8A- 6



Payload Summary

8A- 7

Payload Component	Technology	Quantity	Beams per Antenna	Capacity per Beam	Capacity per Satellite
TSL Uplink Antenna	Luneberg Lens	1	1450 (725 LHCP, 725 RHCP)	16 E1s (33 Mbps)	23,200 E1s (47.8 Gbps)
TSL Downlink Antenna	Phased Array	8	2 (1 LHCP, 1 RHCP)	112 E1s (229.4 Mbps)	1,792 E1s (3.7 Gbps)
GSL Uplink Antenna	Phased Array	1	8 (4 LHCP, 4 RHCP)	300 E1s (614.4 Mbps)	2,400 E1s (4.9 Gbps)
GSL Downlink Antenna	Phased Array	1	8 (4 LHCP, 4 RHCP)	300 E1s (614.4 Mbps)	2,400 E1s (4.9 Gbps)
ISL	Optical Laser	8	1 (2 x 815 Mbps channels)	796 E1s (1.63 Gbps)	6,368 E1s (13.0 Gbps)
Fast Packet Switch	Semiconduct or	1	--	--	4,882 E1s (10 Gbps)

Beacon

- Aids in time & frequency synchronization
  - Transmits ephemeris and footprint information for self and 8 neighbors
    - Position vector
    - Velocity vector
    - Time reference
  - 1 kb/s data rate
  - Updates every 10 sec

BER Allocation

8A- 9

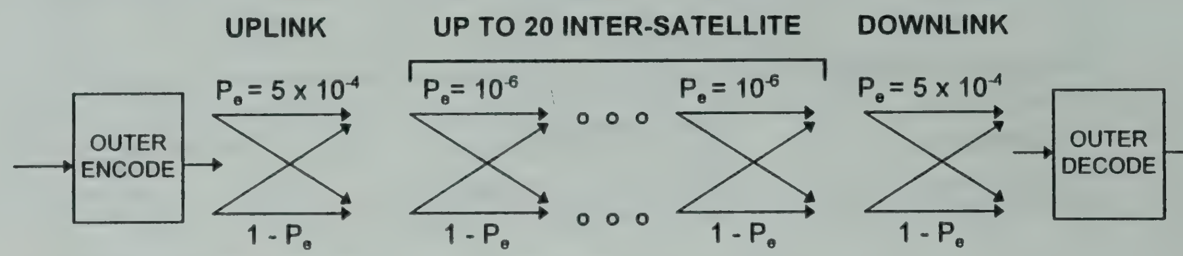


Figure 3.1-8. LINK BER ALLOCATION

Table 3.1-2. TSL Waveform BER Requirements

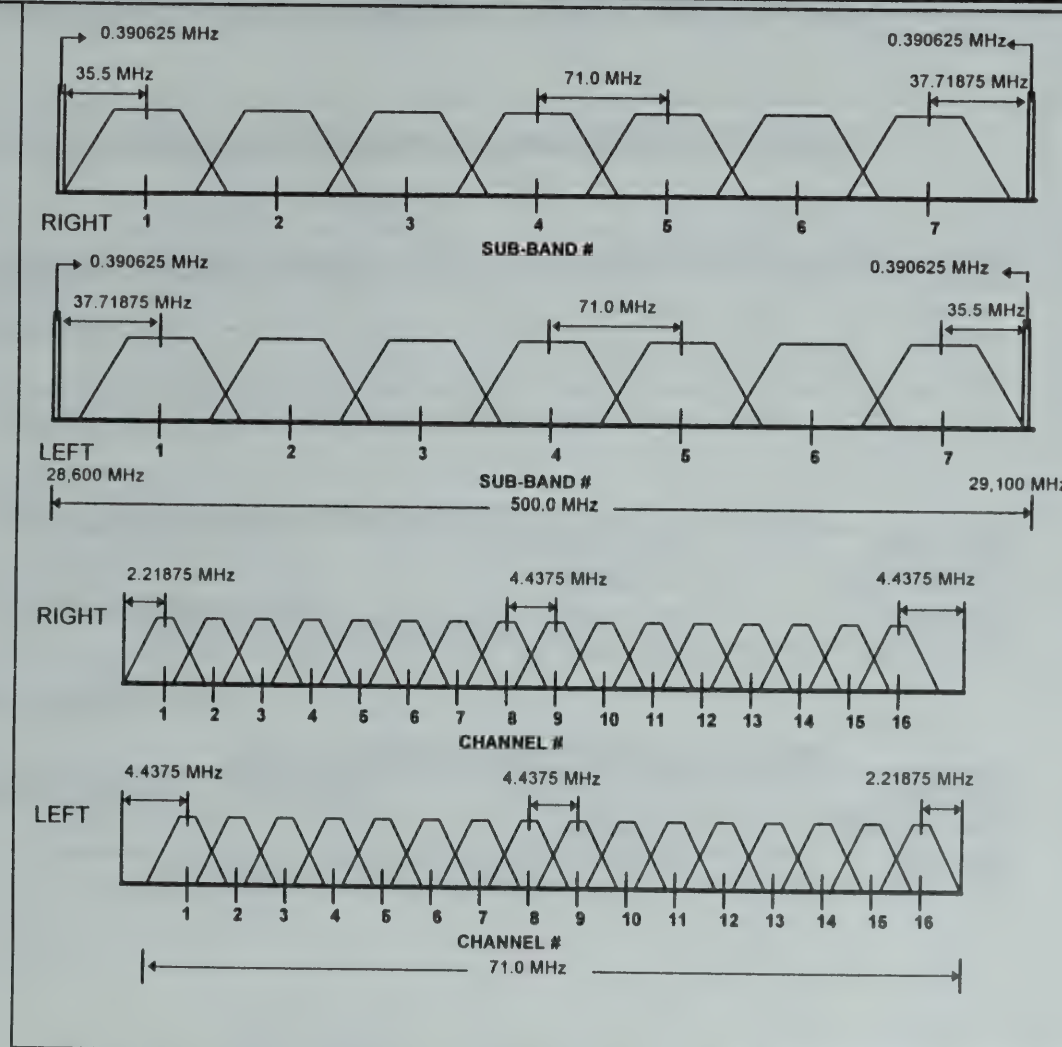
Data BER	10^{-10} end to end
Header BER	10^{-11} per link
ISL BER	10^{-6} per link (assuming a maximum of 20 links)

Table 3.2-3. GSL Waveform BER Requirements

Data BER	10^{-10} end to end
Header BER	10^{-13} per link
ISL BER	10^{-6} per link (assuming a maximum of 20 links)

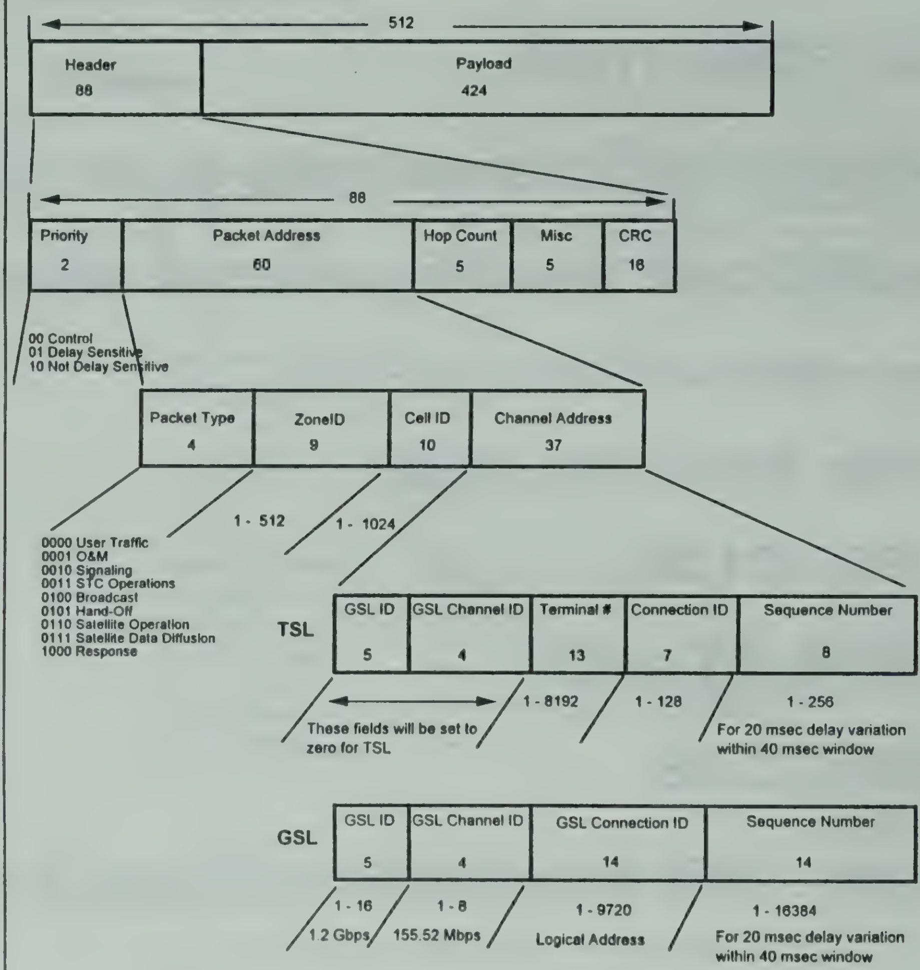
TSL Uplink Frequency Plan

8A- 10



Packet Format

8A- 11



Teledesic Packet

Figure 3.3.2.1.1.3-2

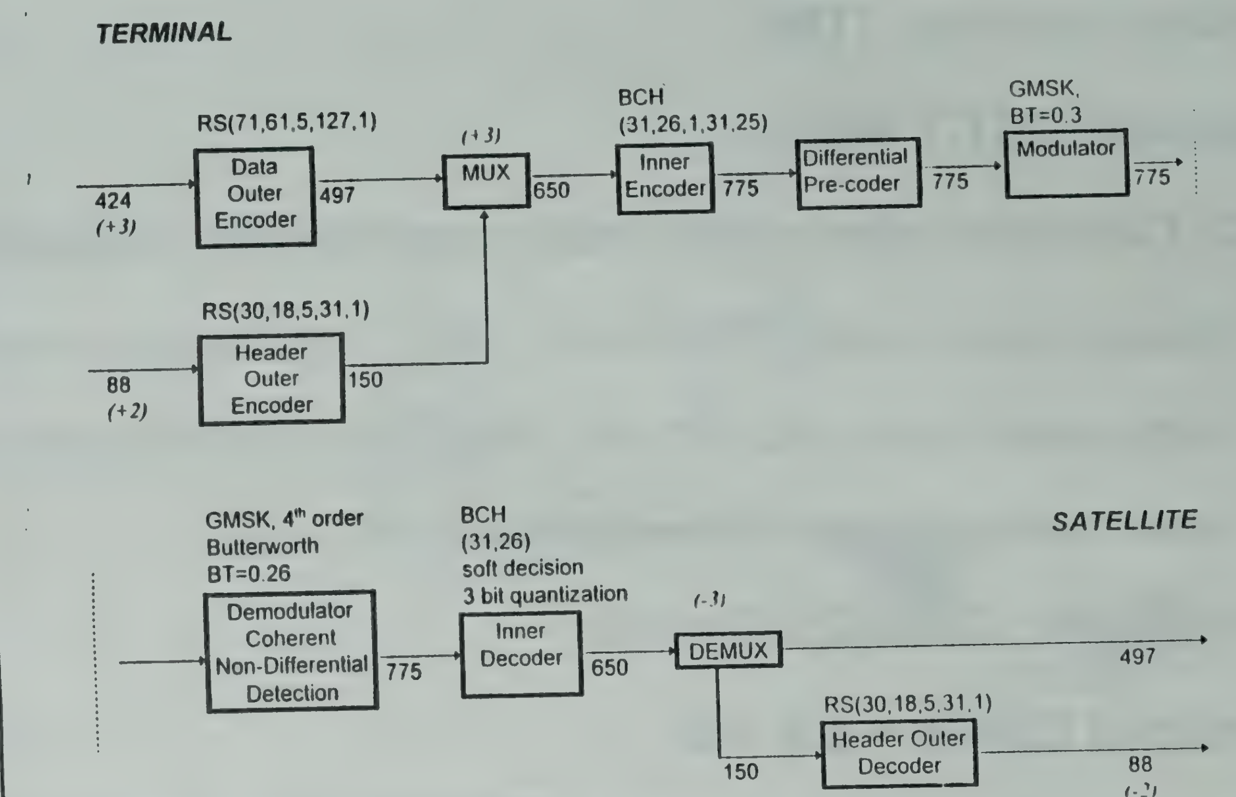
TSL Uplink Characteristics

8A- 12

- Multiple access: FDMA/TDMA
- Data rate: 2.048 Mb/s (Subchannel rates down to 4 kb/s)
- FEC: Concatenated code (header protected separately)
  - Header outer code: R-S (30,18), $GF(2^5)$
  - Data outer code: R-S (71,61), $GF(2^7)$
  - Inner Code: BCH (31,26)
- Modulation: GMSK, BT = 0.3
- Required Eb/No = 7.3 dB
- Burst symbol rate: 3.986 Ms/s (includes guard time between packets)

TSL Uplink Coding Frame

8A- 13



- $(+\eta)$ indicates the number of stuff bits to be added
- $(-\eta)$ indicates the number of stuff bits subtracted

Figure 3.1-6. Uplink Waveform Coding And Modulation

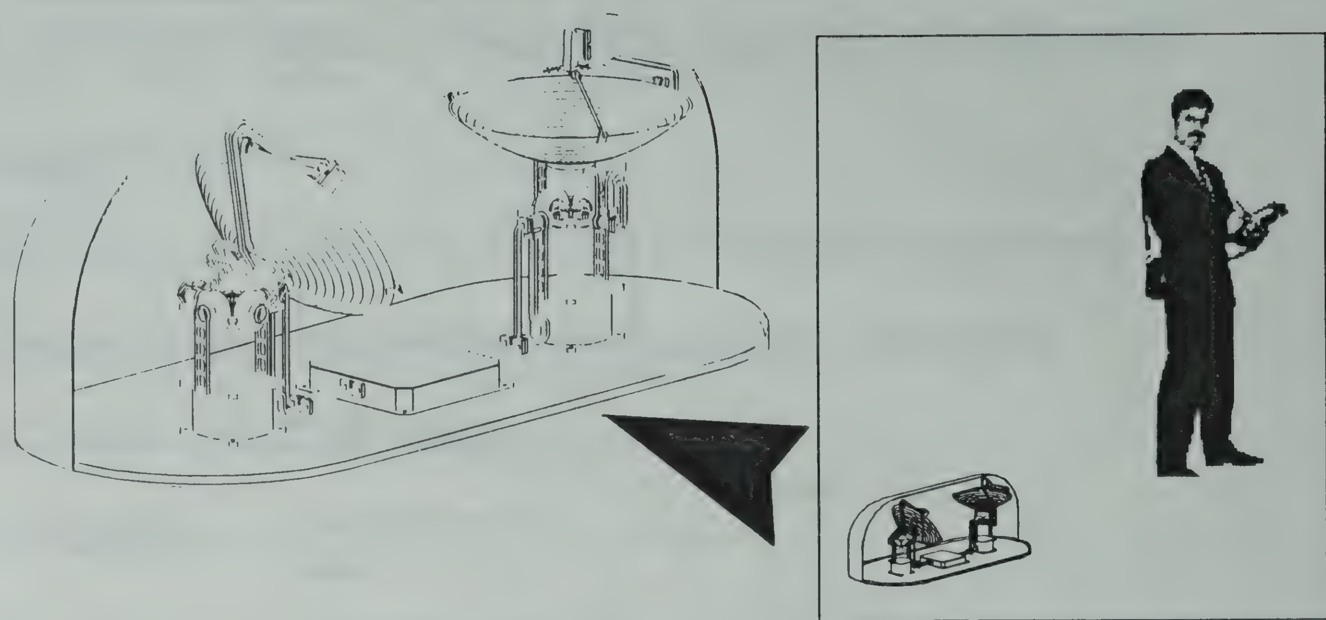
TSL Downlink Characteristics

8A- 14

- **Multiple access: TDM**
- **Data rate: 237.7 Mb/s**
- **FEC: Concatenated code (header protected separately)**
  - **Header outer code: R-S (59,51, GF(2^7) (4 headers bundled)**
  - **Data outer code: R-S (71,61), GF(2^7) (4 bundled and interleaved)**
  - **Inner code: 2/3 rate convolutional, k=7**
- **Modulation: GMSK, BT = 0.3**
- **Required Eb/No = 5.6 dB**
- **Transmission rate: 550.068 Ms/s (x1, x1/2, x1/3, x1/4, x1/5)**

Teledesic Standard Terminal (TST)

8A- 15



GSL Frequency Plan

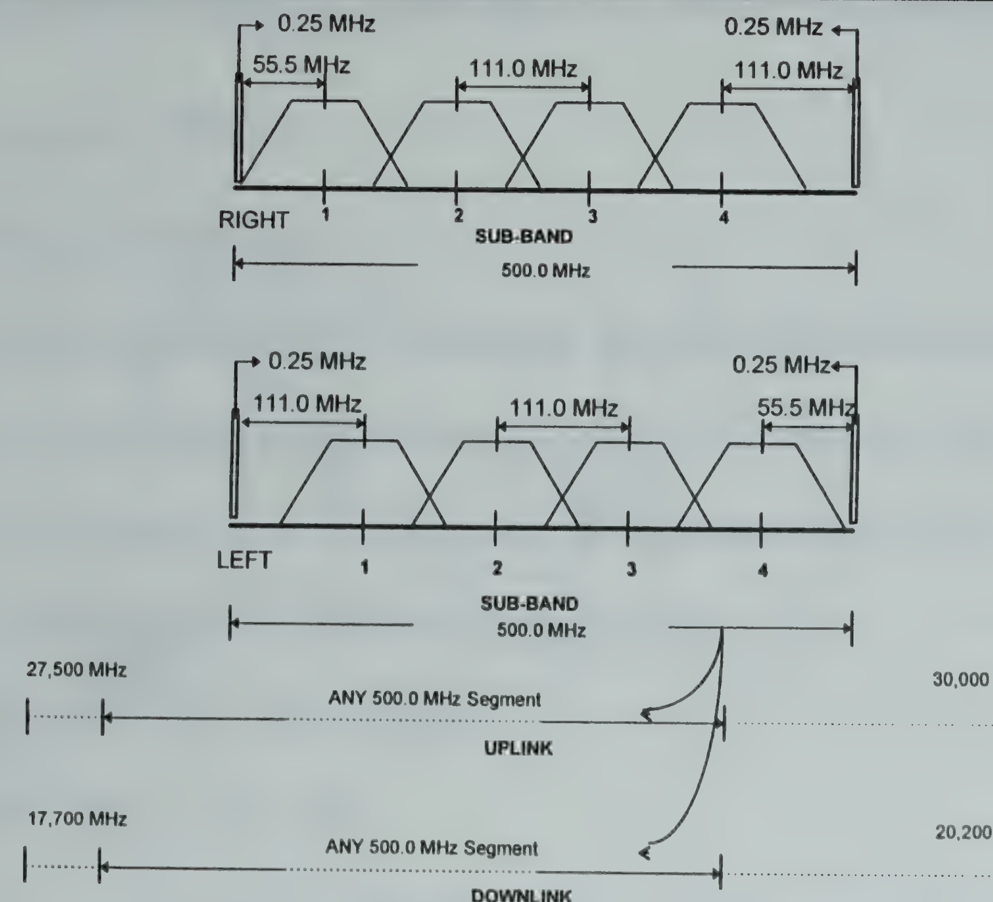


Figure 3.2-1 Channelization For Right And Left Polarizations

GSL Characteristics

8A- 17

- **Multiple access: FDMA/TDMA**
- **Data rate: 155.52 Mb/s (upto 8 channels can be combined)**
- **FEC: Concatenated code**
  - **Header outer code: R-S (67,51), GF(2^7) (4 headers bundled)**
  - **Data outer code: R-S (71,61), GF(2^7) (4 packets bundled)**
  - **Inner code: Trellis code, 64 state**
- **Modulation: 16-QAM**
- **Spectral shape: Raised cosine, β=0.5**
- **Required Eb/No = 8.6 dB**
- **Transmission rate: 79.72 Ms/s**

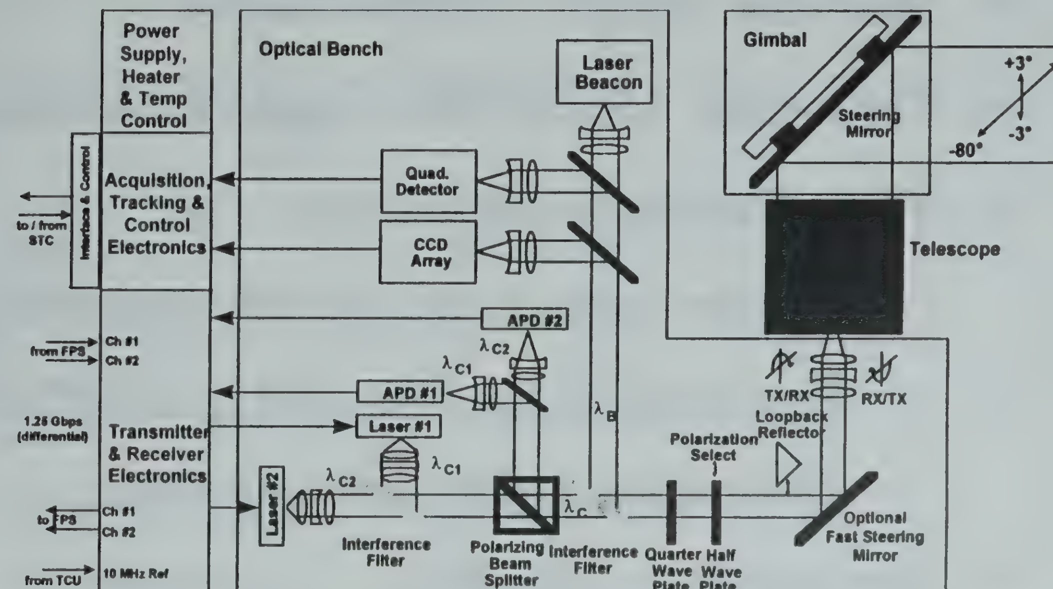
ISL Characteristics

8A- 18

BER = 10-6

Data Rate = 2.4 Gb/s

Optical link



Teledesic Summary

Lots of satellites

Lots of very complex satellites

Some invention required

Commercial Satellite Communication Applications
Course No. 9SV109

Module 8B
Golbal Broadcast Service
GBS

October 24, 1997

Boeing Information, Space, & Defense Systems

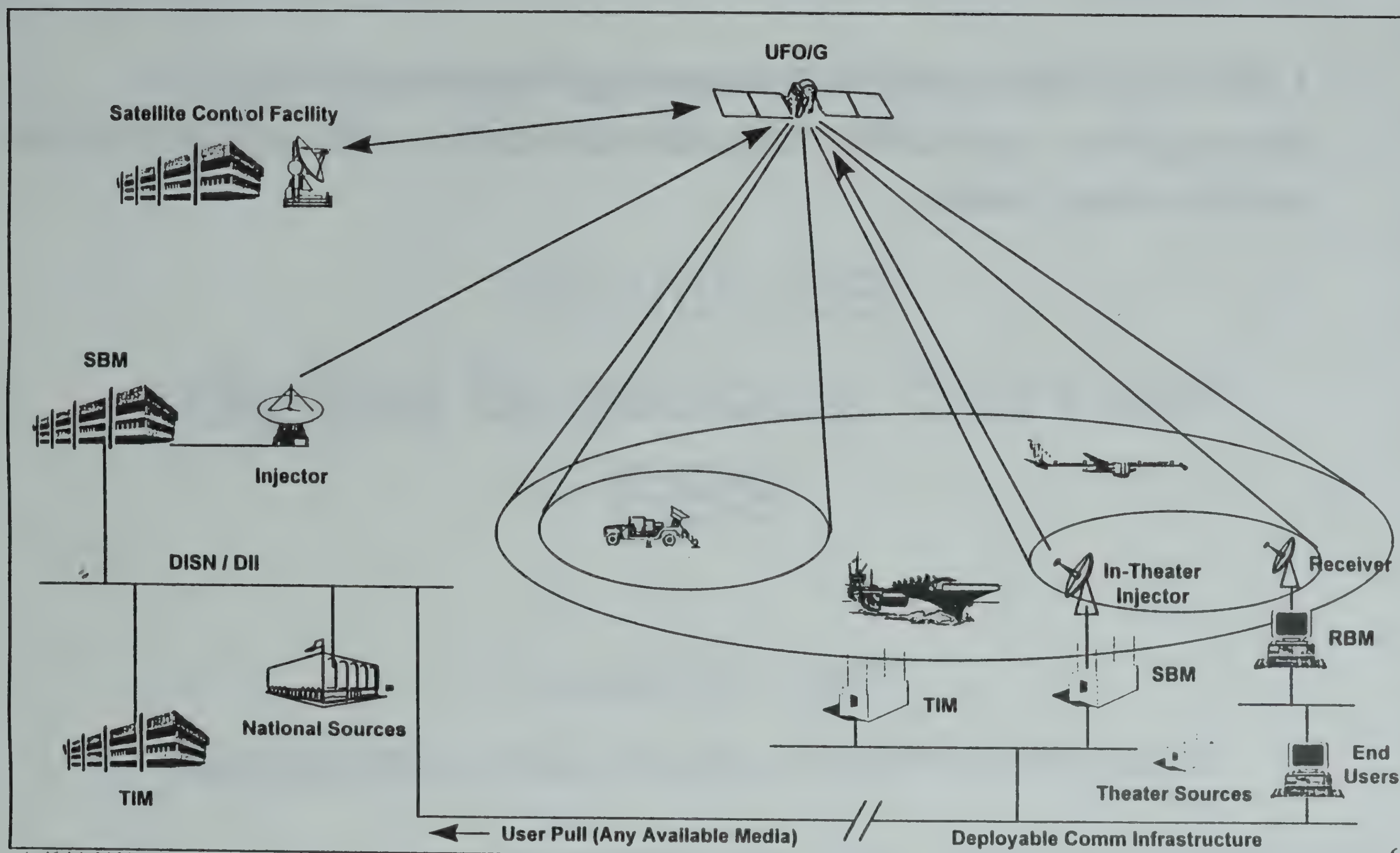
GBS Concept

8B- 2

- **Leverage commercial technology to provide high throughput, low-cost communications to the military on a world-wide basis**

GBS Architecture

8B- 3



Constellation and Coverage

8B- 4

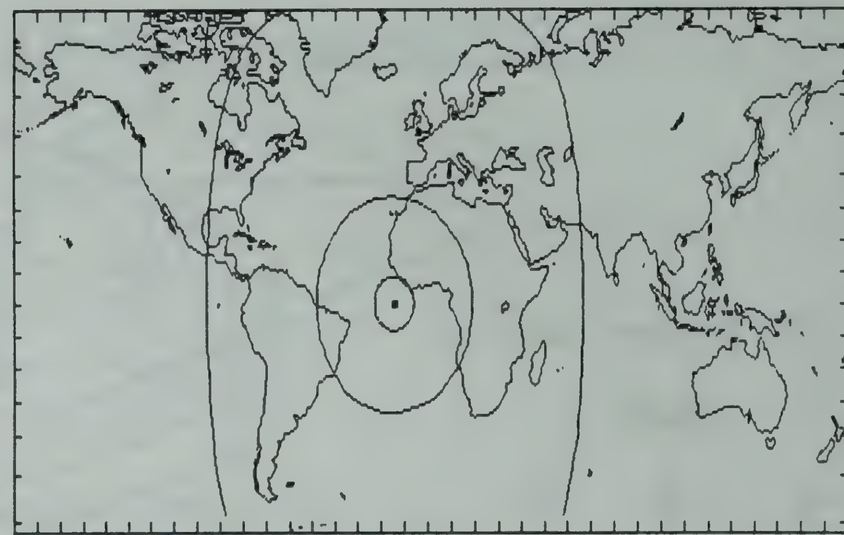
3 satellites

Altitude - GEO

Inclination - 5° at insertion

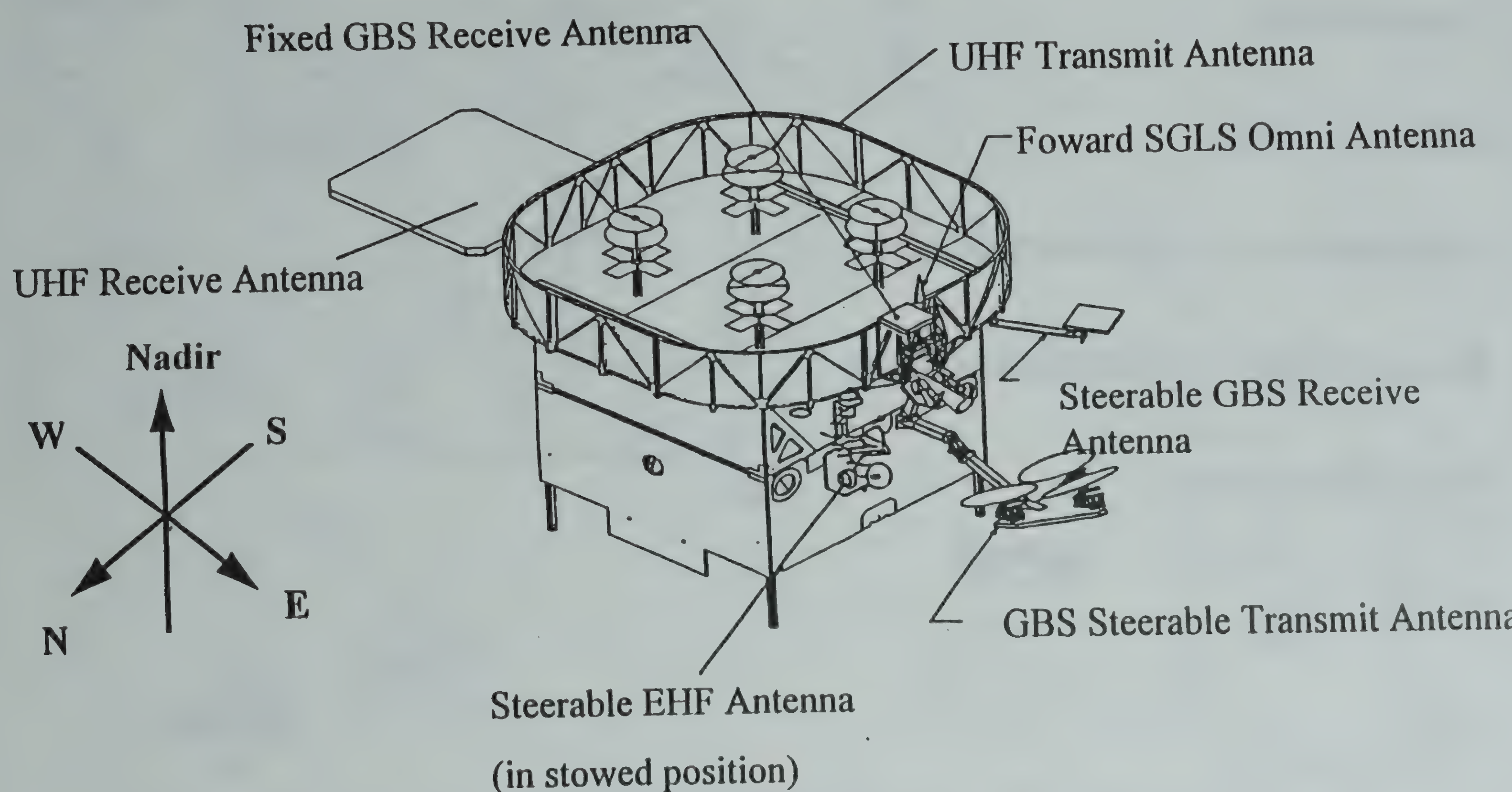
Eccentricity - 0.005 at insertion

<u>Not station kept</u>



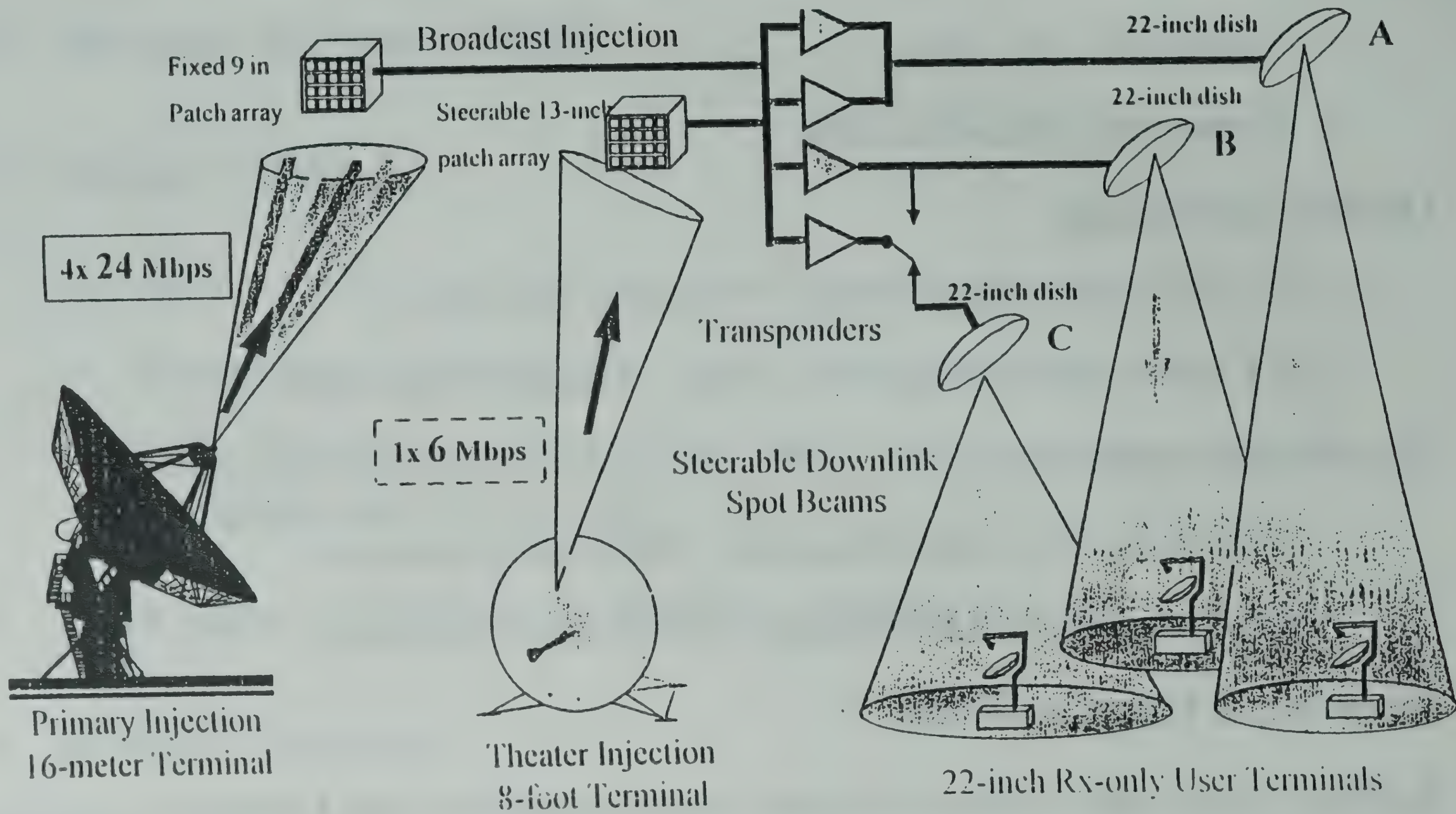
GBS Satellite

8B- 5



GBS Configuration

8B- 6



Payload Description

Ka-band operation

- Uplink 30 - 31 GHz
- Downlink 20.2-21.2 GHz

Uplink antennas

- 9 inch fixed patch array - Primary Injection
- 13 inch steerable patch array - Theater Injection

Downlink antennas

- Two steerable spot-beams - 500 nmi coverage
- One steerable spot-beam - 2000nmi coverage

Bent-pipe transaponder

Earth coverage beacon to aid in acquisition and antenna pointing

Secondary payload for UFO satellite operations

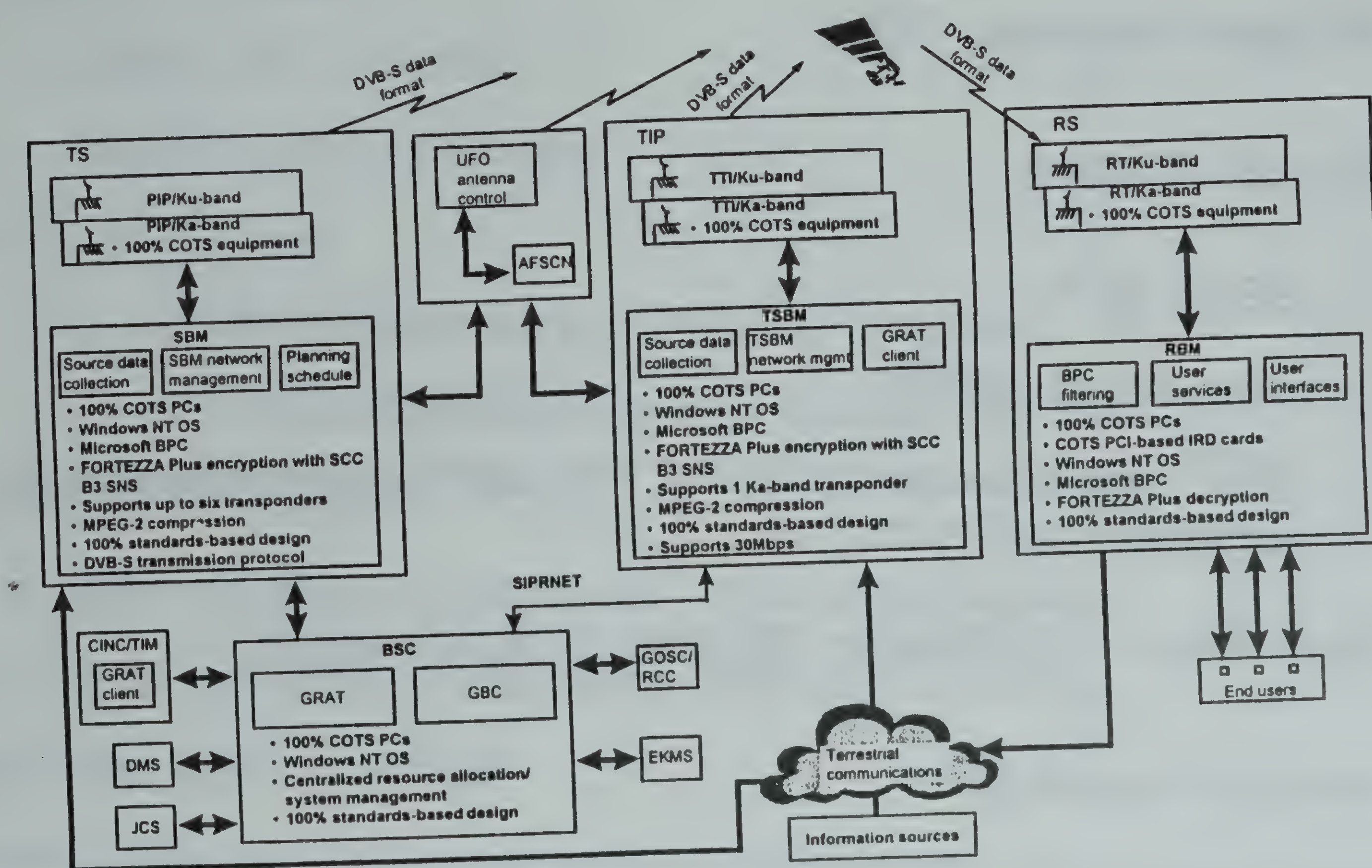
GBS Signal

8B- 8

- **Multiple Access - TDM**
- **Signal - DVB-S**
  - **BER < 10^{-10}**
  - **Modulation - QPSK**
  - **FEC - Concatenated R-S(204,188) and Convolutional, k=7, variable rate 1/2, 2/3, 3/4,**
- **Data Rate - 1.5 Mb/s to 30 Mb/s (1 kb/s steps)**
- **MPEG-2 framing**

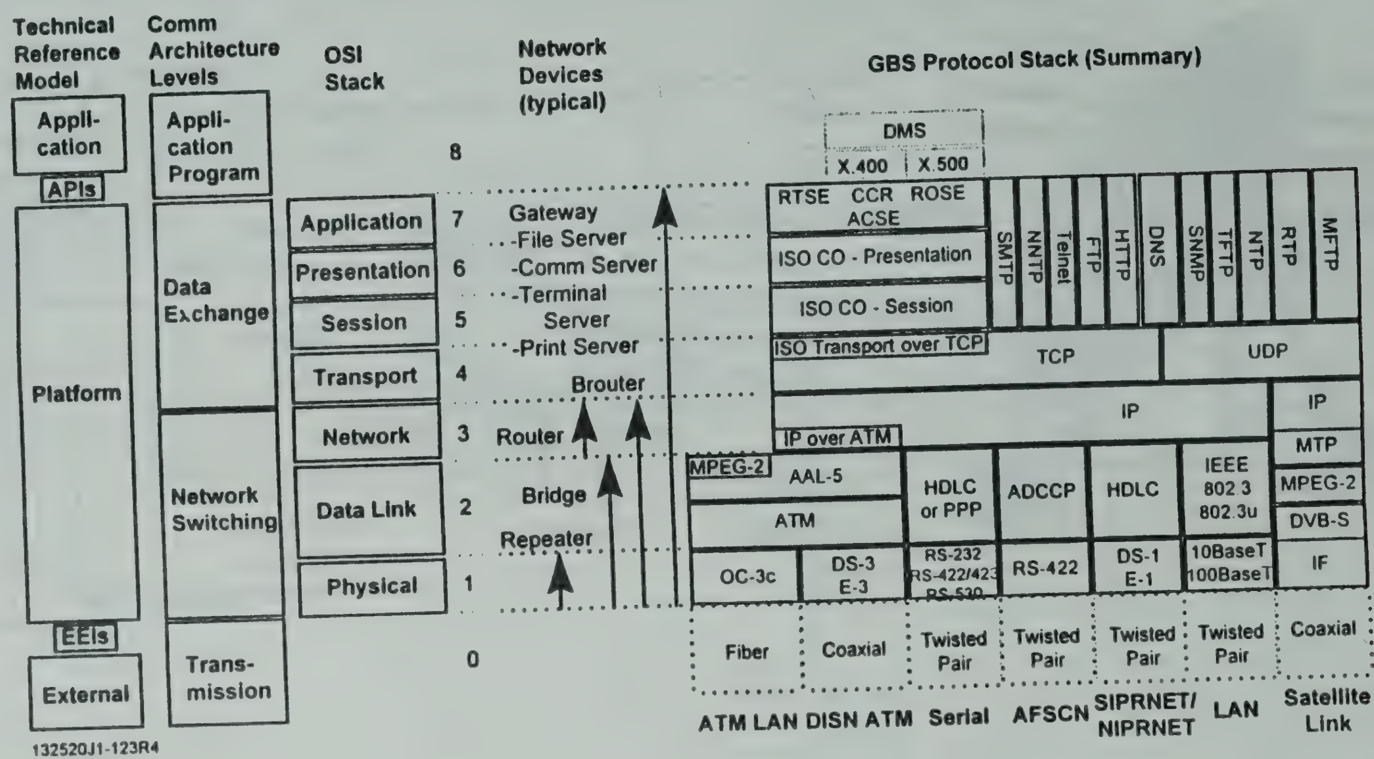
Commercial Emphasis

8B- 9



Network Layering

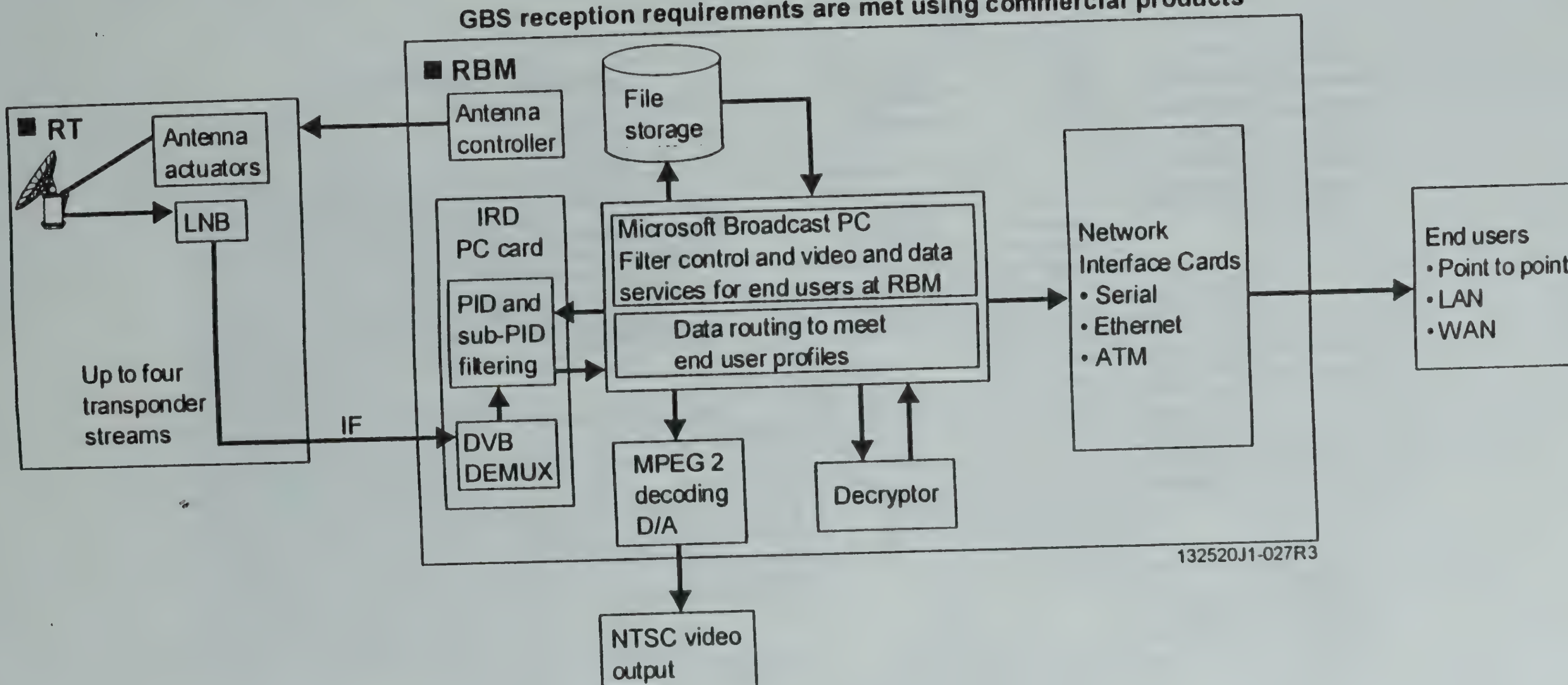
8B- 10



RBM Block Diagram

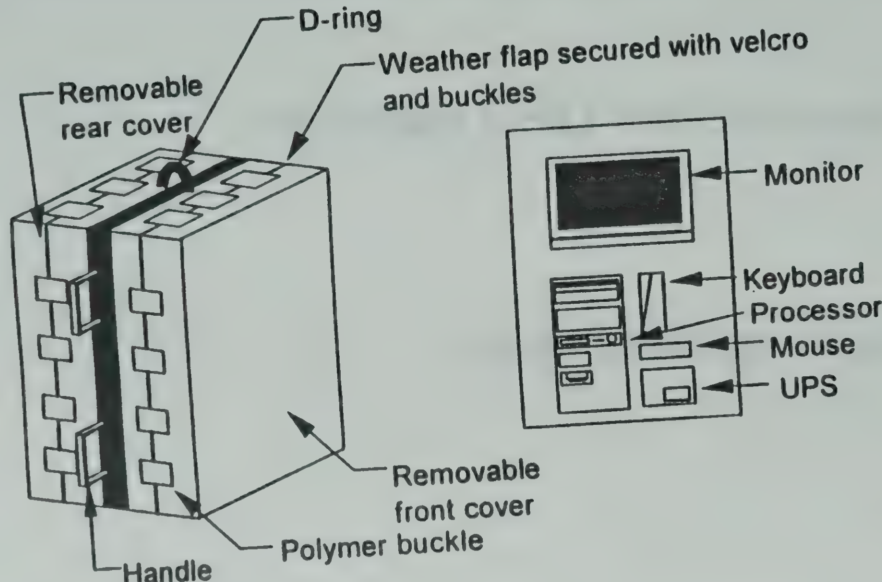
8B- 11

GBS reception requirements are met using commercial products



Receiver Suite

8B- 12



GBS Summary

- Military communications system leveraging commercial technology to provide high-rate, low-cost communications
- Phase II uses secondary payload on UFO satellite
  - Not station-kept
  - Requires antenna tracking by ground units

Commercial Satellite Communication Applications
Course No. 9SV109

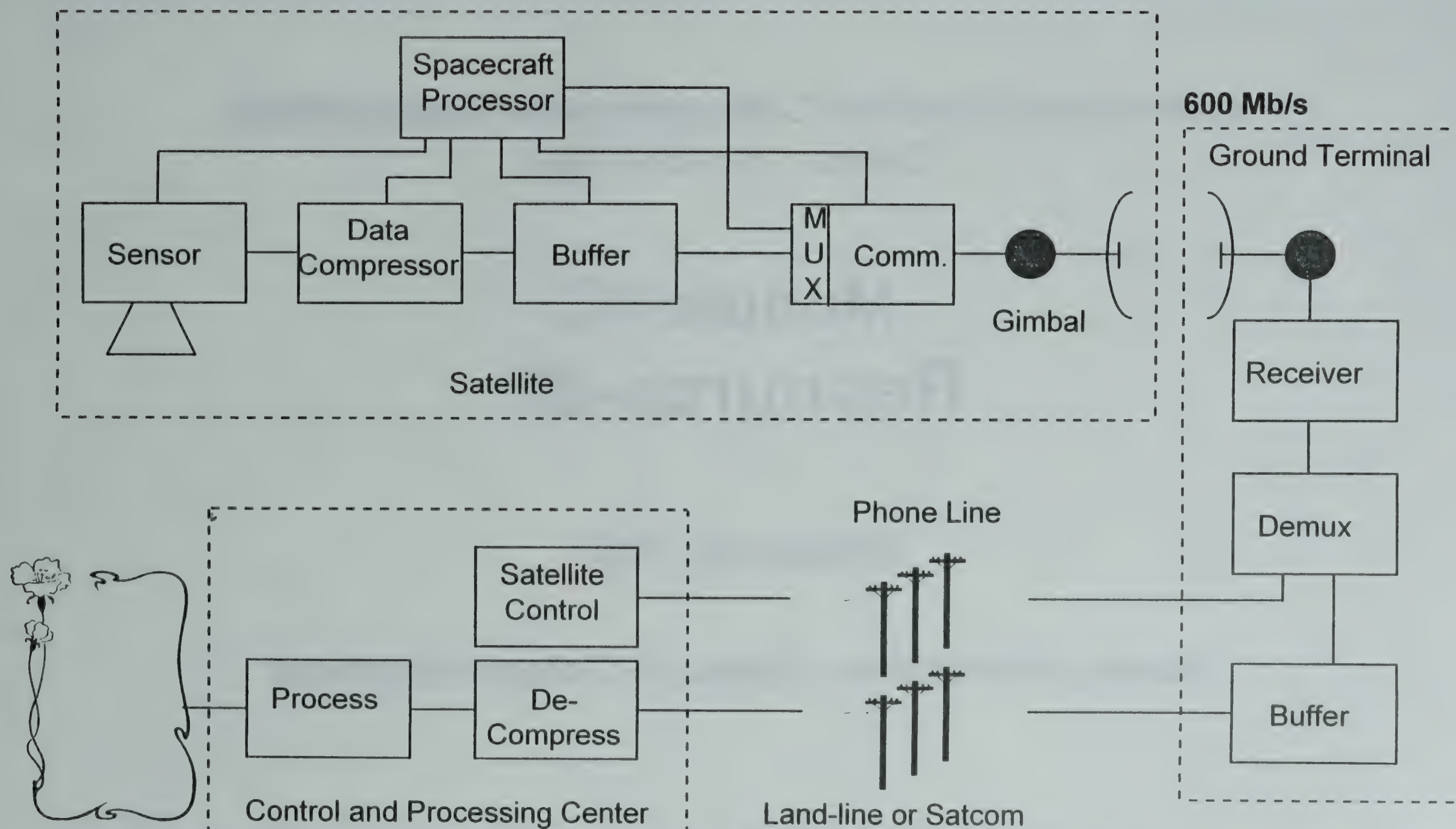
Module 8C
Resource-21

October 24, 1997

Boeing Information, Space, & Defense Systems

System Architecture

8C- 2



Satellite Description

8C- 3

Constellation

- 4 Satellites

Orbit

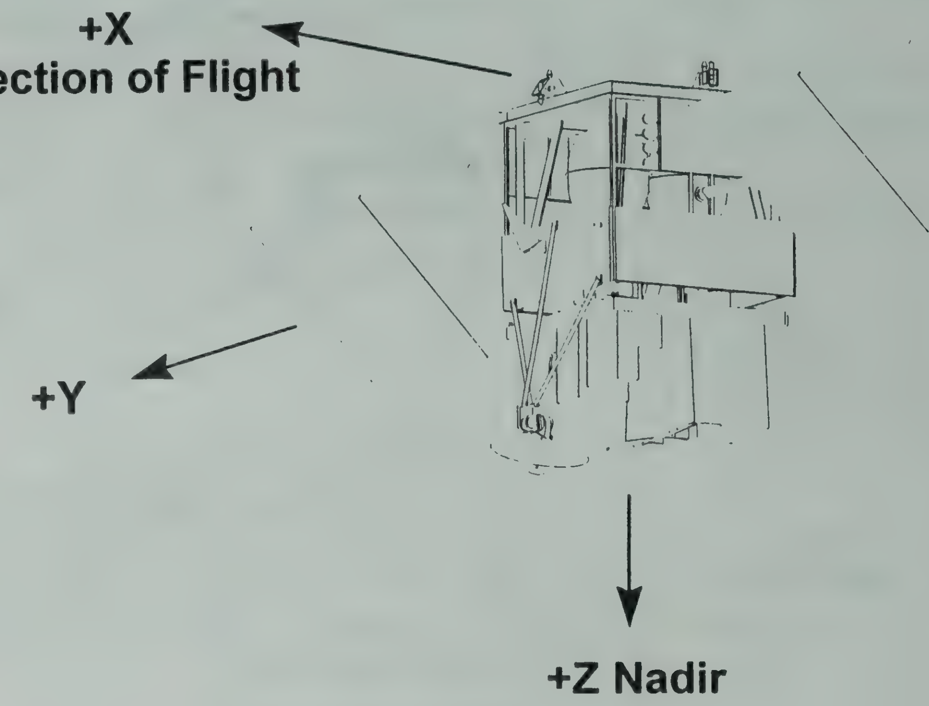
- 743 km
- Sun-synchronous

Satellite

- Weight - 2600 lbs.
- Image Resolution - 10 m
- Coverage - 345 km swath

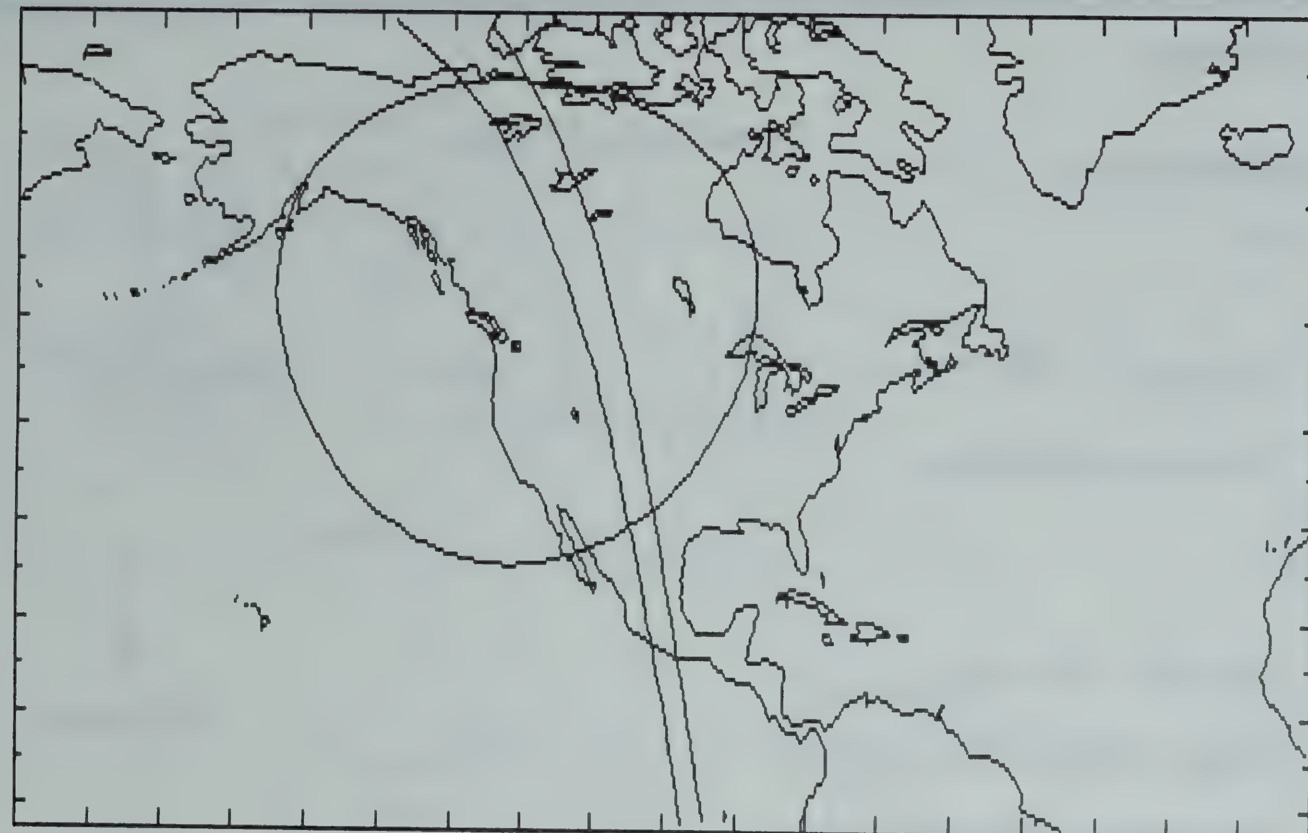
Comm Visibility

- 11.9 Min (5º elevation)



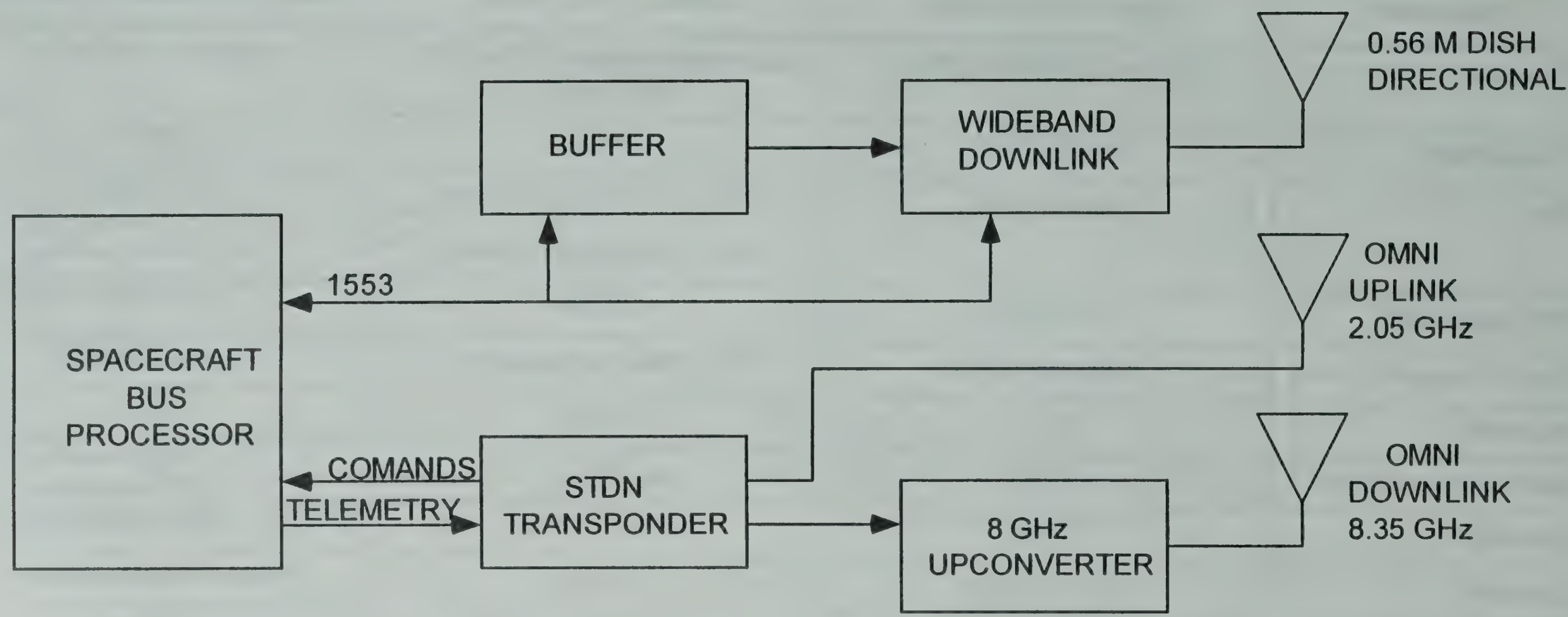
Satellite Coverage

8C- 4



Communication Subsystem

8C- 5



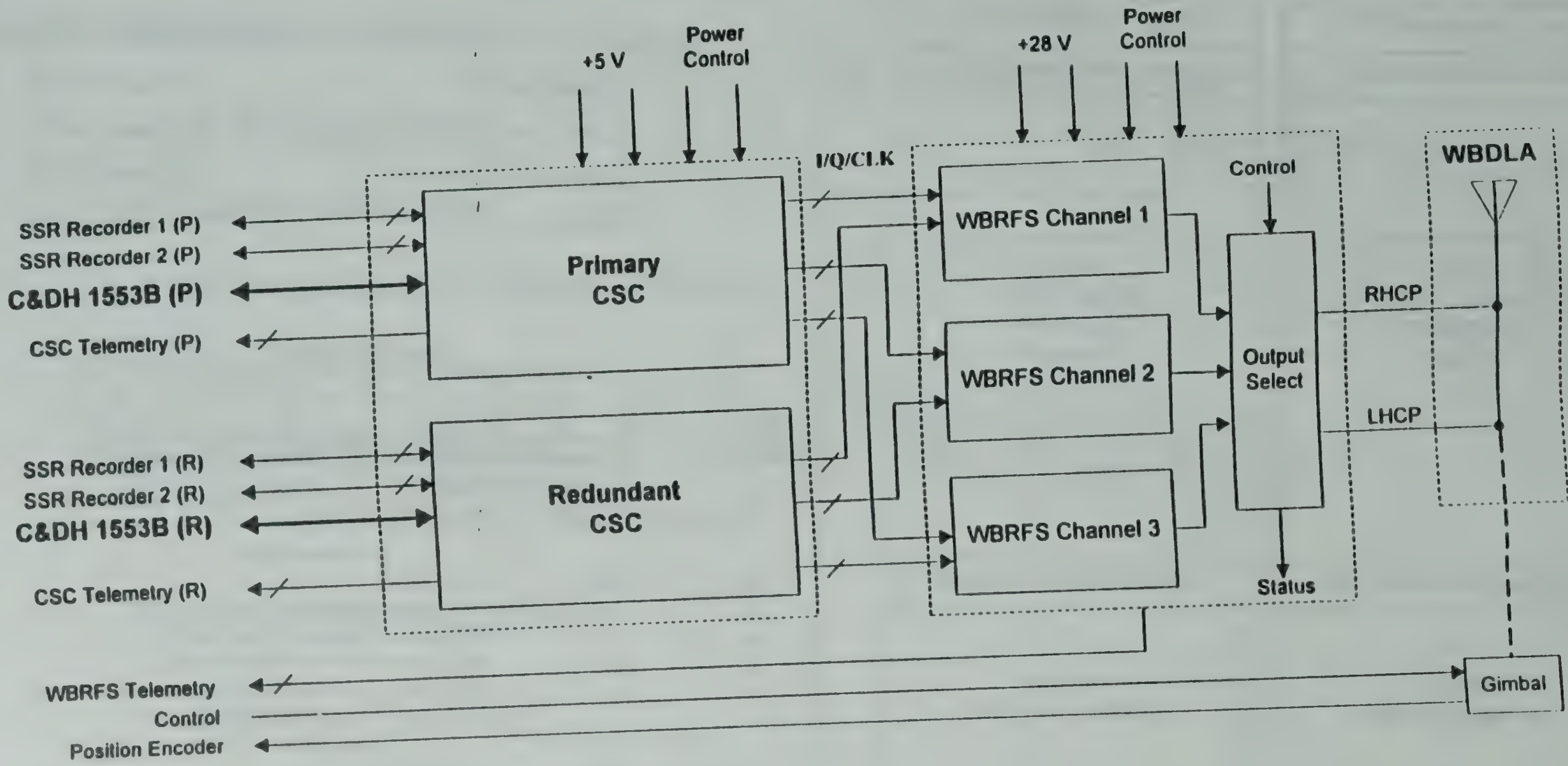
Signal Description

8C- 6

Parameter	X-Band WB Downlink	S-Band TT&C Uplink	X-Band NB Telemetry Downlink
Frequency	8185 to 8190 MHz (TBD)	Dual frequencies in 2025–2110 MHz range	8350 MHz ± 125 kHz
Polarization	RHCP/LHCP	RHCP	LHCP
EIRP	+31.72 dBW	+31 ± 1 dBW (normal ops) +41 ± 1 dBW (emergency)	-9.00 dBW
RIP (estimated)	–154 dBW	-136 dBW	–199 dBW
Carrier frequency offset	Up to 200 kHz	Up to 200 kHz (assumed)	Up to 200 kHz
Subcarrier	N/A	16 kHz	N/A
Subcarrier modulation	N/A	PM	N/A
Bandwidth	375 MHz	4 kHz (TBD)	32 kHz (TBD)
Data rate	2 x 324 Mbps	2 kbps	8 kbps; 128 kbps (option)
Modulation	Offset QPSK	PM/PCM/PSK-M (STDN)	BPSK
Error correction	FEC coding (RS 255,239)	Convolutional coding - on/off	Convolutional coding - on/off
Encryption	Data Encryption Standard (DES)	TBD	TBD
Bit error rate	10^{-10}	10^{-5}	10^{-5}

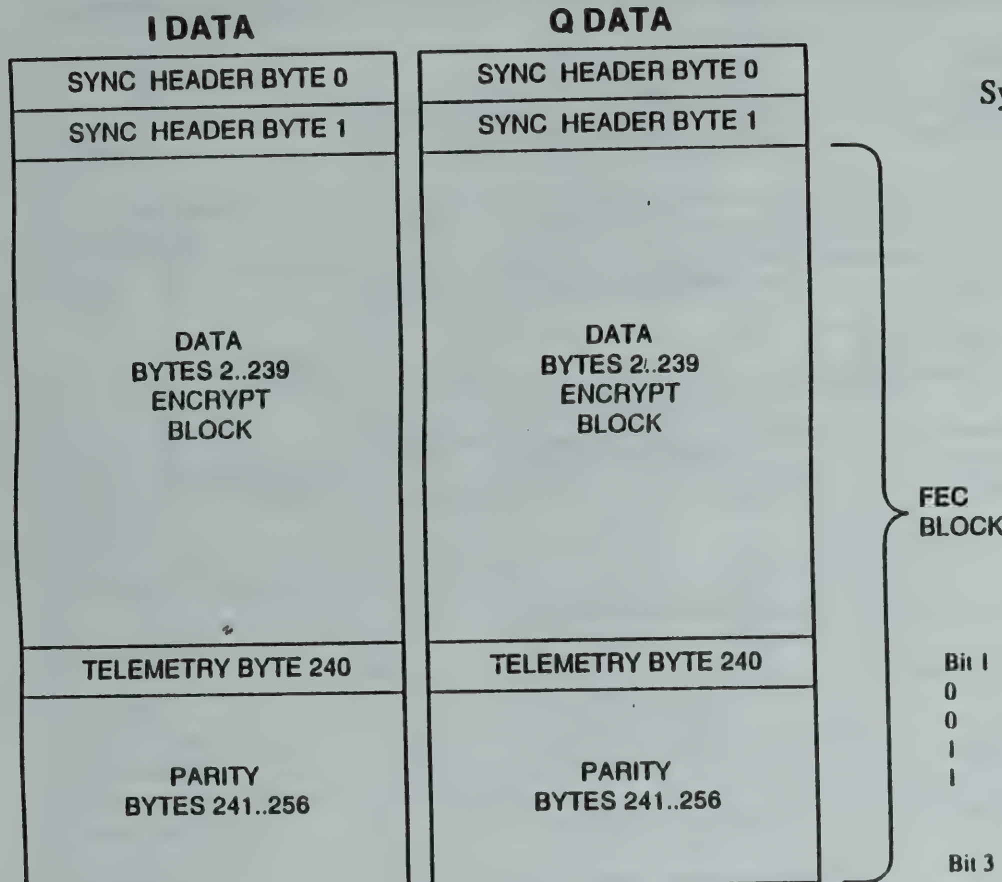
Wideband Downlink

8C- 7



Data Block Format

8C- 8



Sync Header1 = 1ACFFC1D	Sync Header2 = B83FF35E
I Data 0 = 1D	I Data 0 = 5E
I Data 1 = FC	I Data 1 = F3
Q Data 0 = CF	Q Data 0 = 3F
Q Data 1 = 1A	Q Data 1 = B8

Telemetry Format

7	6	5	4	3	2	1	0
Real Time Telemetry from 1553 Interface				Data Type		Encryption Index	

Encryption Index

Bit 1	Bit 0	Description
0	0	Encryption aligned at boundary
0	1	Encryption aligned at 2 byte down
1	0	Encryption aligned at 4 byte down
1	1	Encryption aligned at 6 byte down

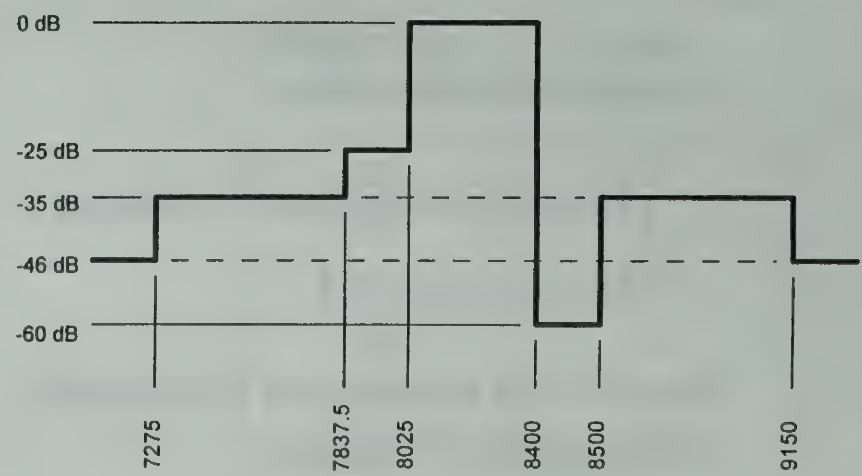
Data Type

Bit 3	Bit 2	Description
0	0	Fill or synchronization Data
0	1	Image data
1	0	Image data with fill data to complete frame
1	1	Not defined

8C- 9

Neighboring Deep-Space Band

- Deep-Space Band
  - 8.4 to 8.5 GHz
  - Large Antenna
  - Cryogenically cooled pre-amp
  - Goldstone, Ca.
  - ITU-R Rec 578 limit
    - -220 dBW/Hz interference
- Interference mitigation
  - Spectral Filtering
  - Antenna Pattern



Compression

8C- 10

- **Numerically Lossless**
- **Compression rate**
  - **Highly dependent on image**
  - **Nominally - 2:1**
- **Single bit error can scramble large part of image**

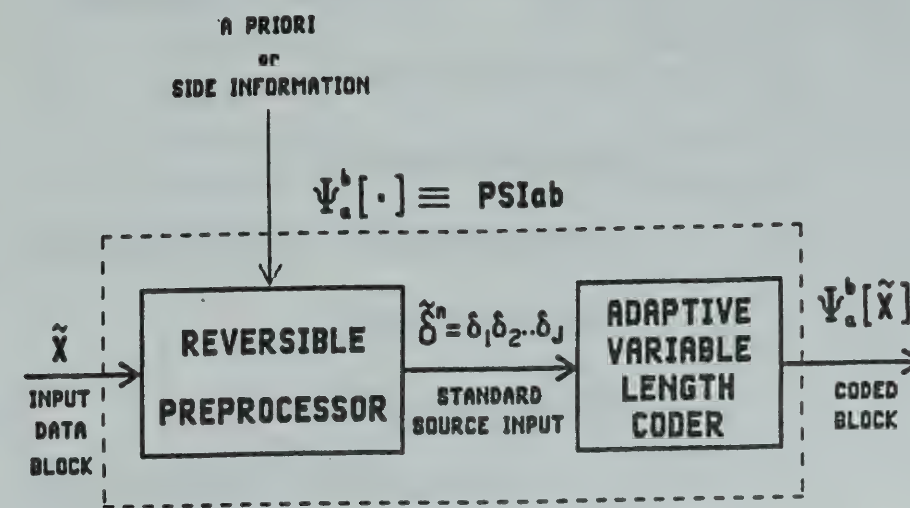


Fig. 1. General Coding Module

Lossless Compressor

8C- 11

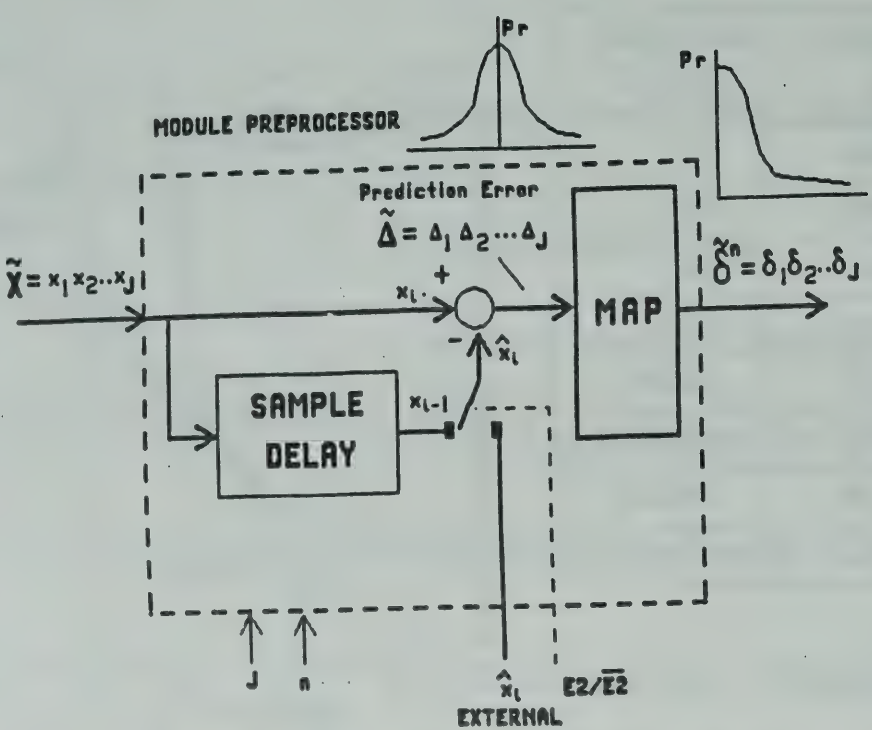


Fig. 5 Built-in Preprocessor Functional Block Diagram

Table 1. Basic Mapping of Δ_i into the Integers, δ_i

Prediction Error, Δ_i	Integer δ_i
0	0
-1	1
+1	2
-2	3
+2	4
-3	5
.	.
.	.
.	.

$$\delta_i = \begin{cases} 2|\Delta_i| - 1 & \text{if } \Delta_i < 0 \\ 2\Delta_i & \text{if } \Delta_i \geq 0 \end{cases}$$

Lossless Compressor (cont)

8C- 12

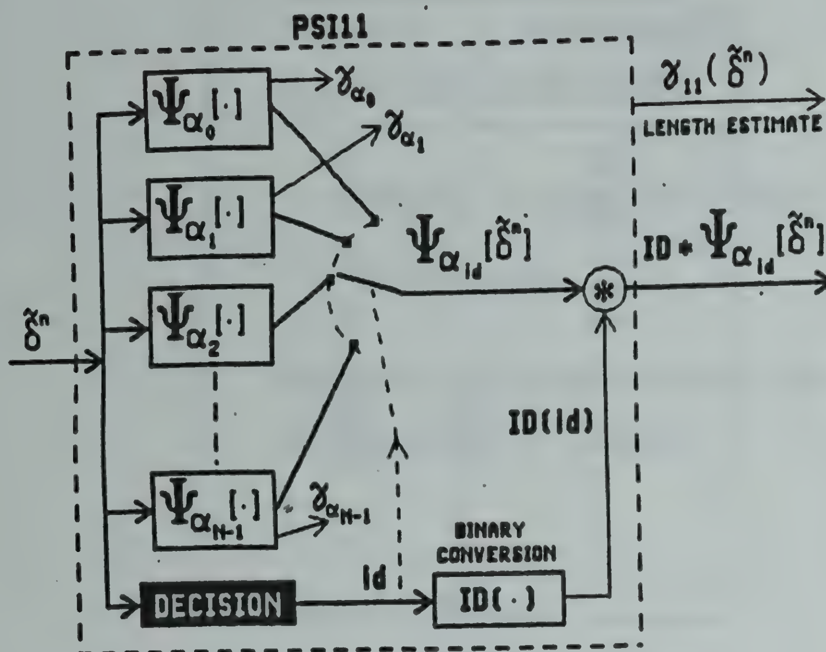


Fig. 7. General-Purpose Adaptive Coder, PSI11

Table 2. 8-Word 3-Tuple Code, cfs[i]

3-tuple β_i	CODE WORD $cfs[\beta_i]$
000	1
001	001
010	010
100	011
011	00000
101	00001
110	00010
111	00011

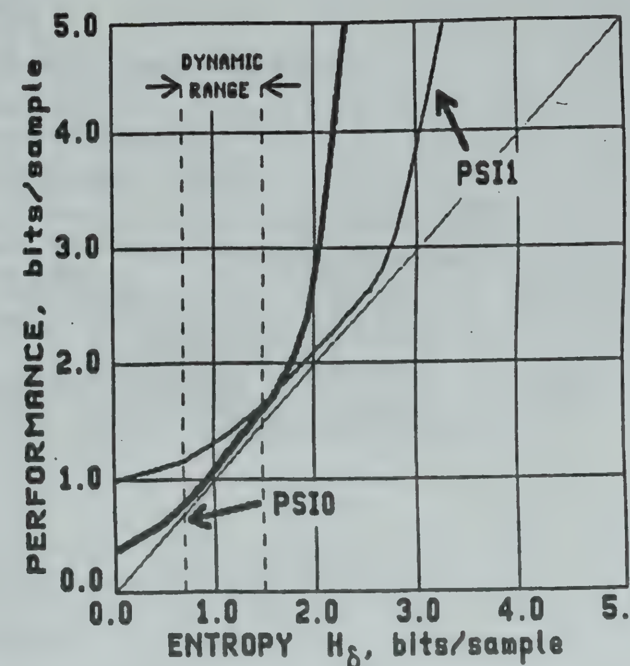


Fig. 9. Average PSI0 Performance

Summary

8C- 13

- Simplex transmitter
- Limited visibility time
  - High-rate data
  - Compressed Image
    - Low bit error probability
- Deep-space band for neighbor
  - Interference mitigation
    - Directional antenna with low sidelobes
    - Spectral filtering

Commercial Satellite Communication Applications
Course No. 9SV109

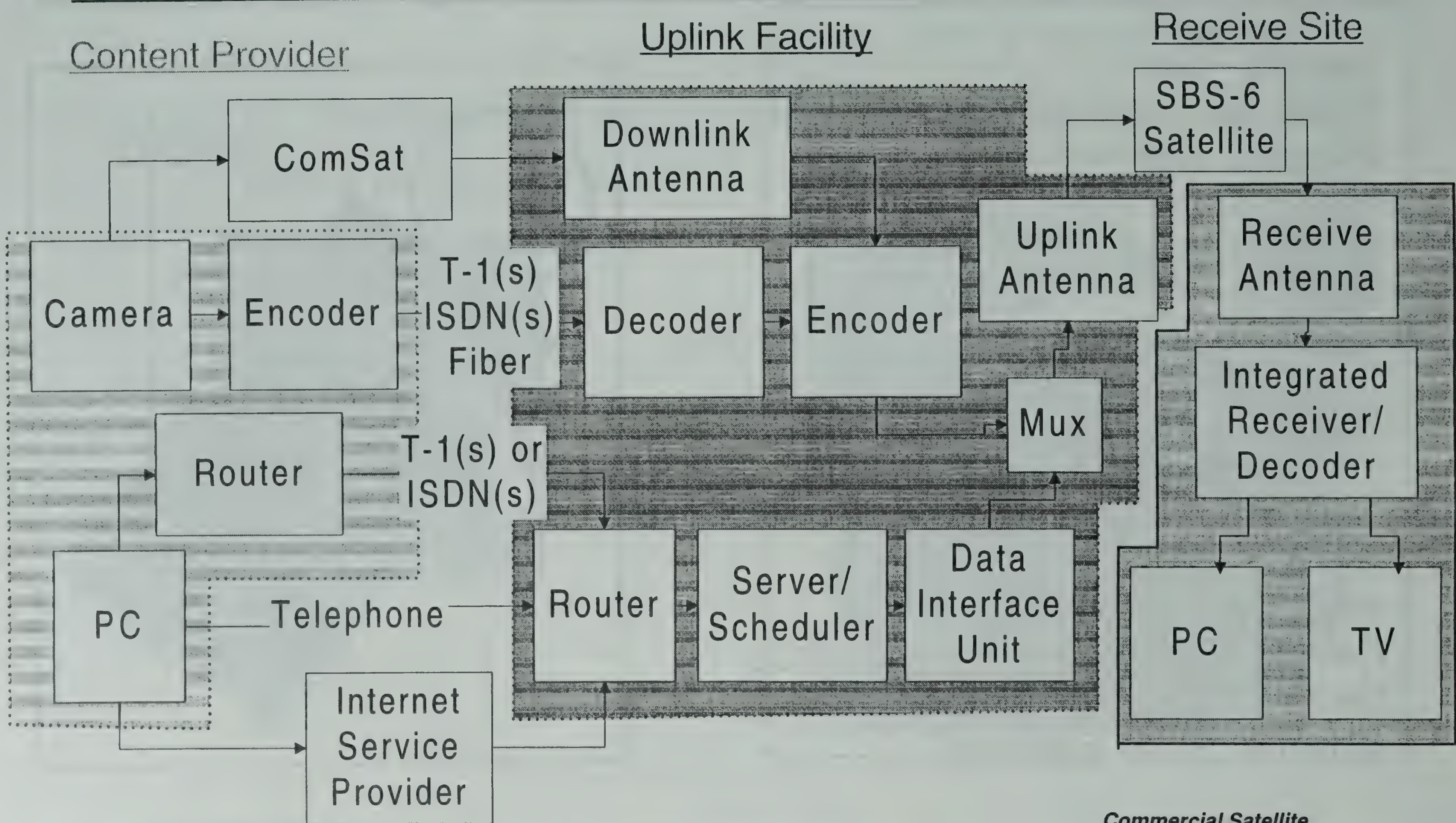
Module 8D

DigitalXpress

DigitalXpress

System Diagram

8D- 2



DigitalXpress
Satellite Description

8D- 3

Bus: HS - 393
Stablization: Spin-stabilized (55 rpm)
Diameter: 3.66 meter
Mass in Orbit: 1484 kg
Launch: October 1990
Location: 74° West Longitude
Transponders: 19 Ku-band (11.7-12.2GHz)
Redundancy: 30 for 19
Polarization: Linear
Transponder Bandwidth: 43 MHz
TWTA* Power: 41 Watts
Antenna: 2.4 meter
Max EIRP: 51 dBW
Power: 2300 W Beginning-of-life (BOL)
Design Life: 10 years
Batteries: Nickel-Hydrogen

DigitalXpress

8D- 4 Satellite Description

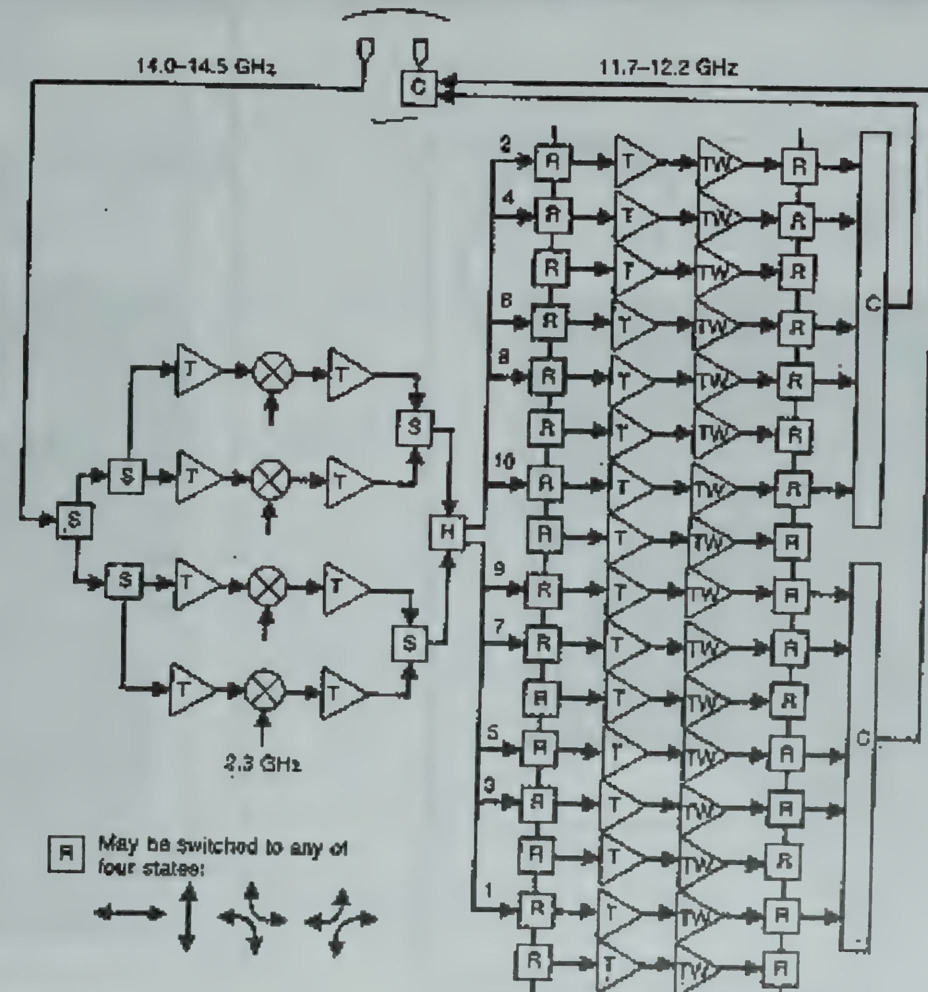
SBS-6 On Orbit

SBS-6 Despun Section

DigitalXpress

8D- 5 Communications Payload

SBS 1 through 4 Communications Payload

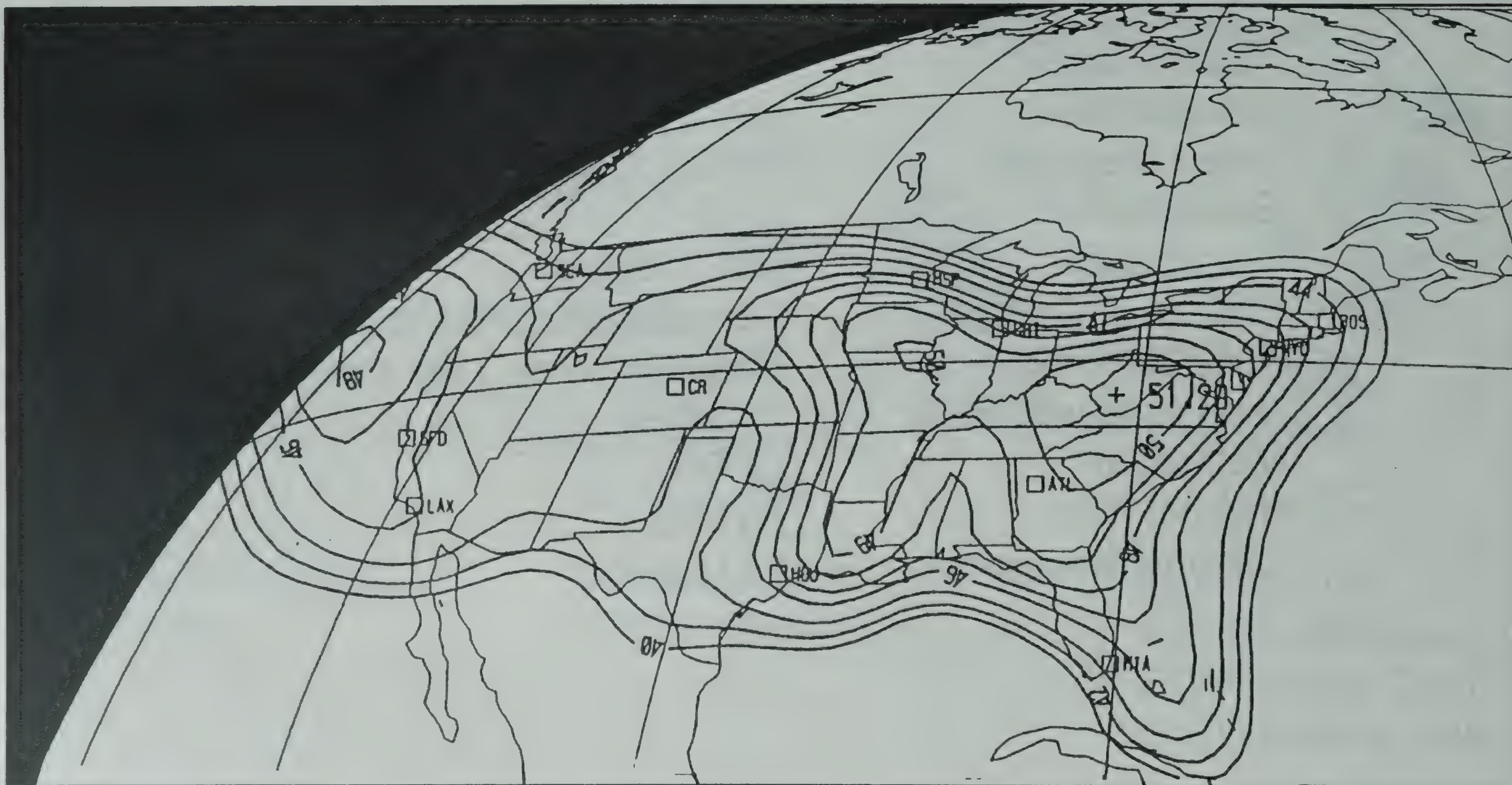


DigitalXpress

Satellite Description

8D- 6

SBS-6 Downlink Footprint



8D- 7

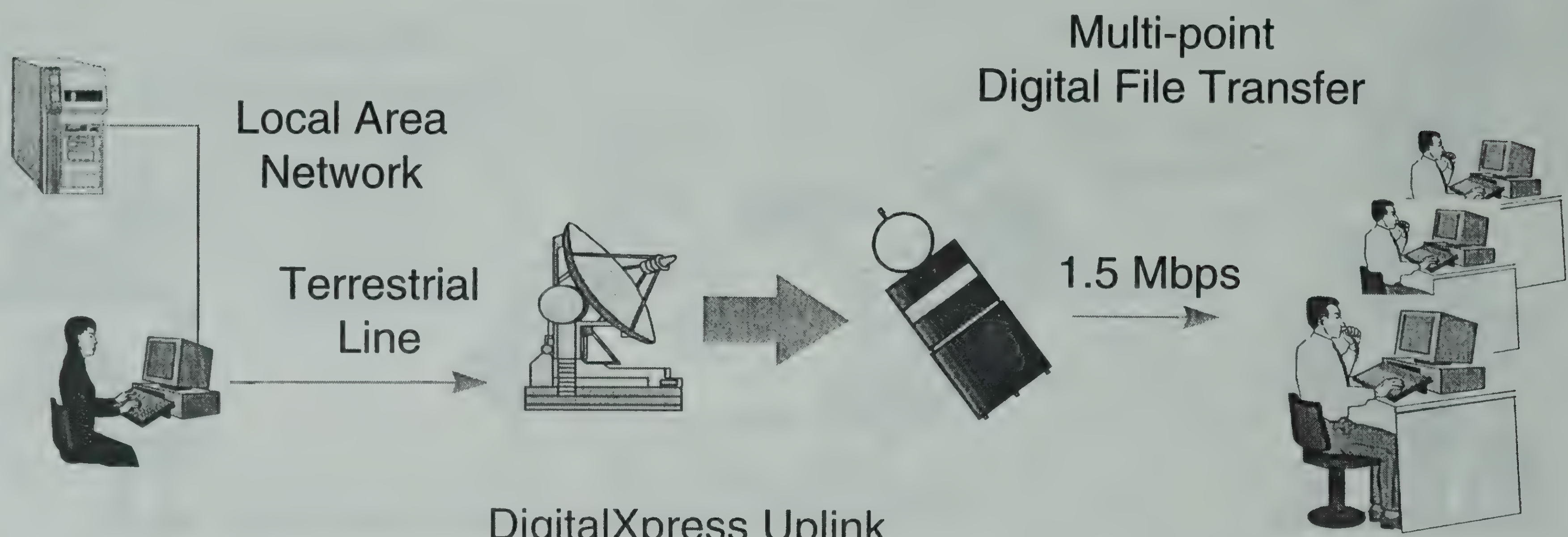
DigitalXpress
Signal Characteristics

Transport Layer:	DSS (proprietary)
Packet Size:	130 bytes
Payload Size:	127 bytes
Video Standard:	MPEG 2, Main Level, Main Profile
Encryption:	DES
Transponder Data Rate:	23.4 Mbps
FEC Inner Code:	Convolutional, R=2/3, K=7
FEC Outer Code:	Reed-Solomon 146, 130 (T=8)
Data Rate with FEC:	40 Mbps
Modulation:	QPSK
Symbol Rate:	20 Msps
Channel Bandwidth:	24 MHz

DigitalXpress

8D- 8

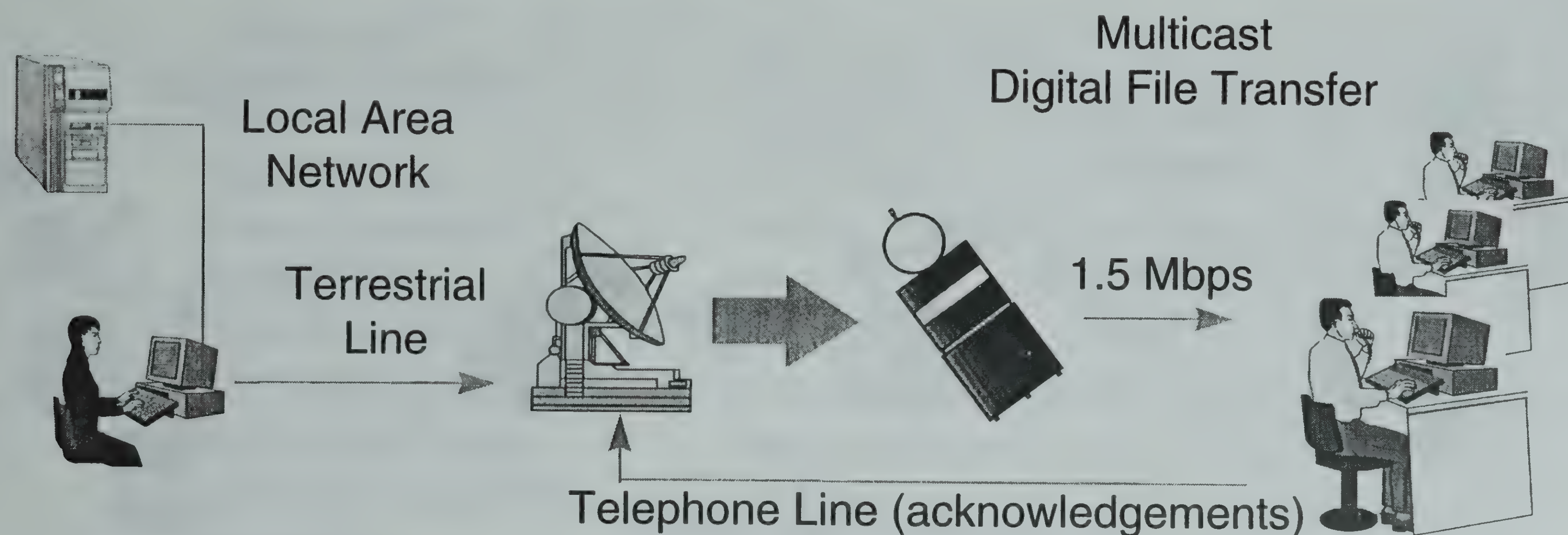
Broadcast File Copy



Submission PC	DigitalXpress Uplink St. Paul, MN	User PC
° Submission S/W ° Modem	° Schedule S/W ° DXP Transmit S/W	° Satellite Dish ° Satellite Receiver ° PC Interface Card ° DXP Receive S/W

DigitalXpress
Multicast File Transfer

8D- 9



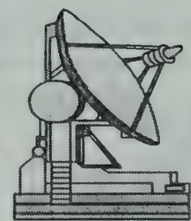
Submission PC	DigitalXpress Uplink St. Paul, MN	User PC
° Submission S/W	° Schedule S/W	° Satellite Dish
° Modem	° COTS Multicast S/W	° Satellite Receiver
	° IP Streams	° PC Interface Card
		° COTS Multicast Receive S/W

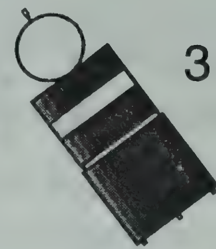
DigitalXpress

Live Video Broadcast

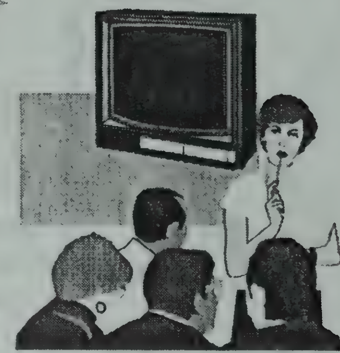
8D- 10

- T-1(s)
- ISDN
- Fiber
- Satellite





3 or 5 Mbps



Submission PC

- Live Video Feed
    - Studio
    - Conf. Rm. Camera
    - Tape
- MPEG 1 or 2 encoder

DigitalXpress Uplink
St.. Paul, MN

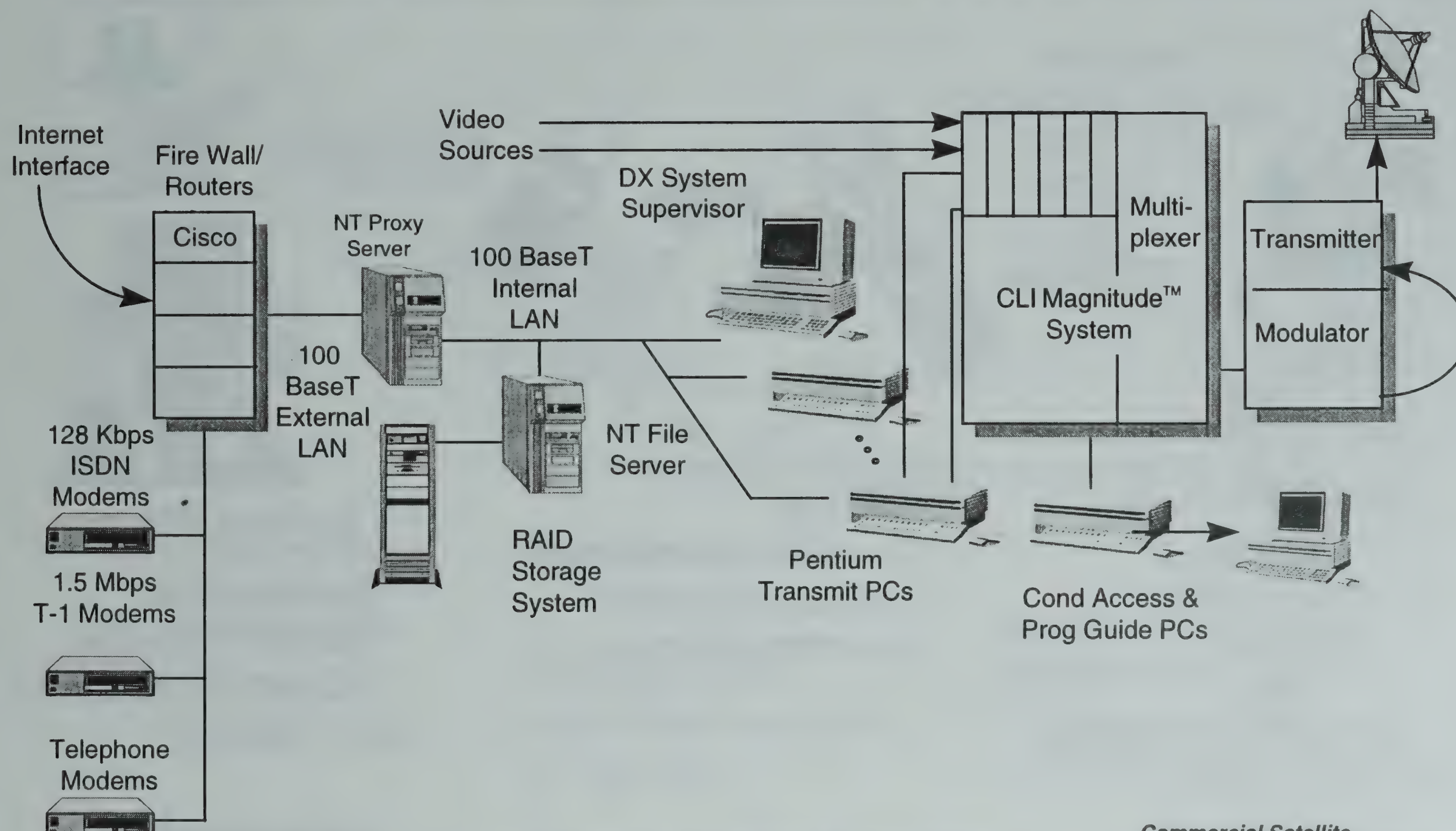
- Decoder
- 3 or 5 Mbps Broadcast
- MPEG 2 Encoder
- Conditional Access

Receive Site

- Satellite Dish
- Satellite Receiver
- PC with Tuner Card or TV monitor

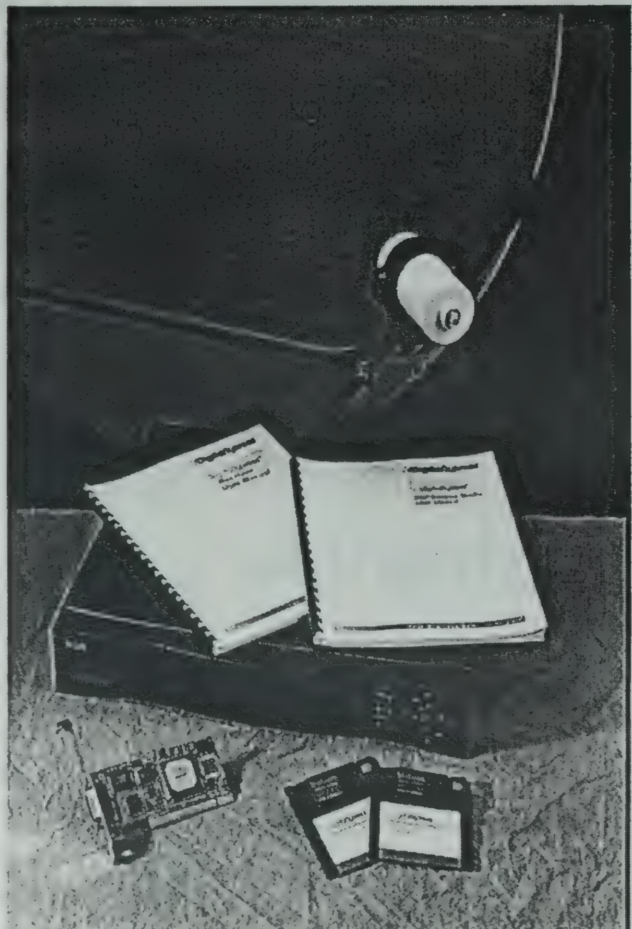
8D- 11

DigitalXpress
Uplink Facility Diagram



DigitalXpress

8D- 12 Receive Equipment Description



Small .9 Meter Dish
- Some U.S. Locations Require 1.2 Meter Dish

DigitalXpress Receiver
- Based on RCA-DSS™ Unit
- DigitalXpress Conditional Access System
- DigitalXpress Program Guide
- Remote Control Unit

Receiver Outputs
- S-Video and Stereo Audio
- Computer - RS 232
- Computer - Wide Band Data Port RS 422

PC Interface Card
- PCI format
- PC Based IRD in Development

Commercial Satellite Communication Applications
Course No. 9SV109

Module 8E

Aviation Information Services

Aviation Information Services

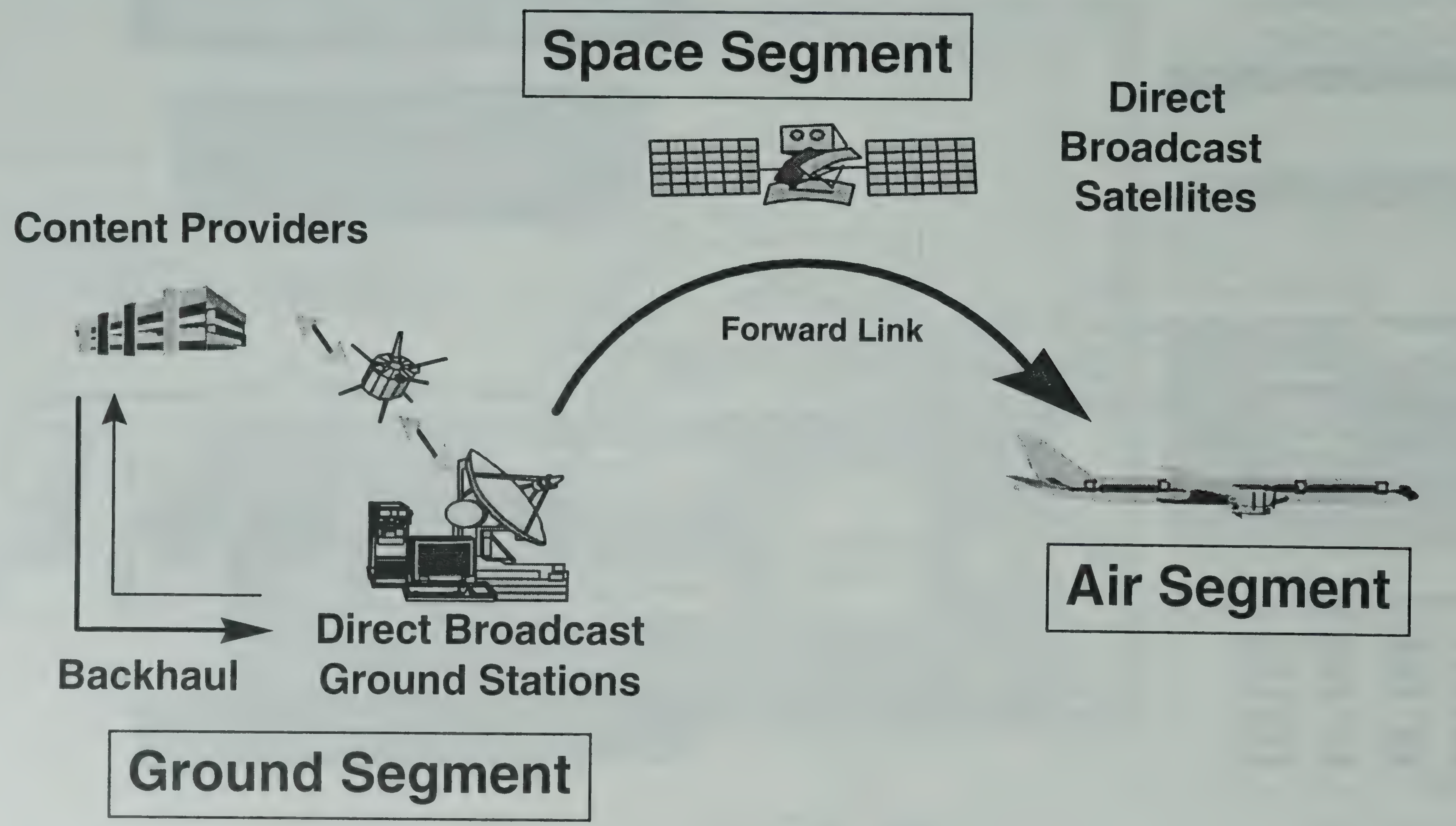
8E- 2

Space Segment Roadmap

- **Near and Mid-term**
  - **Use existing commercial satellite assets**
- **Long Term**
  - **Constellation of MEO satellites**

Aviation Information Services

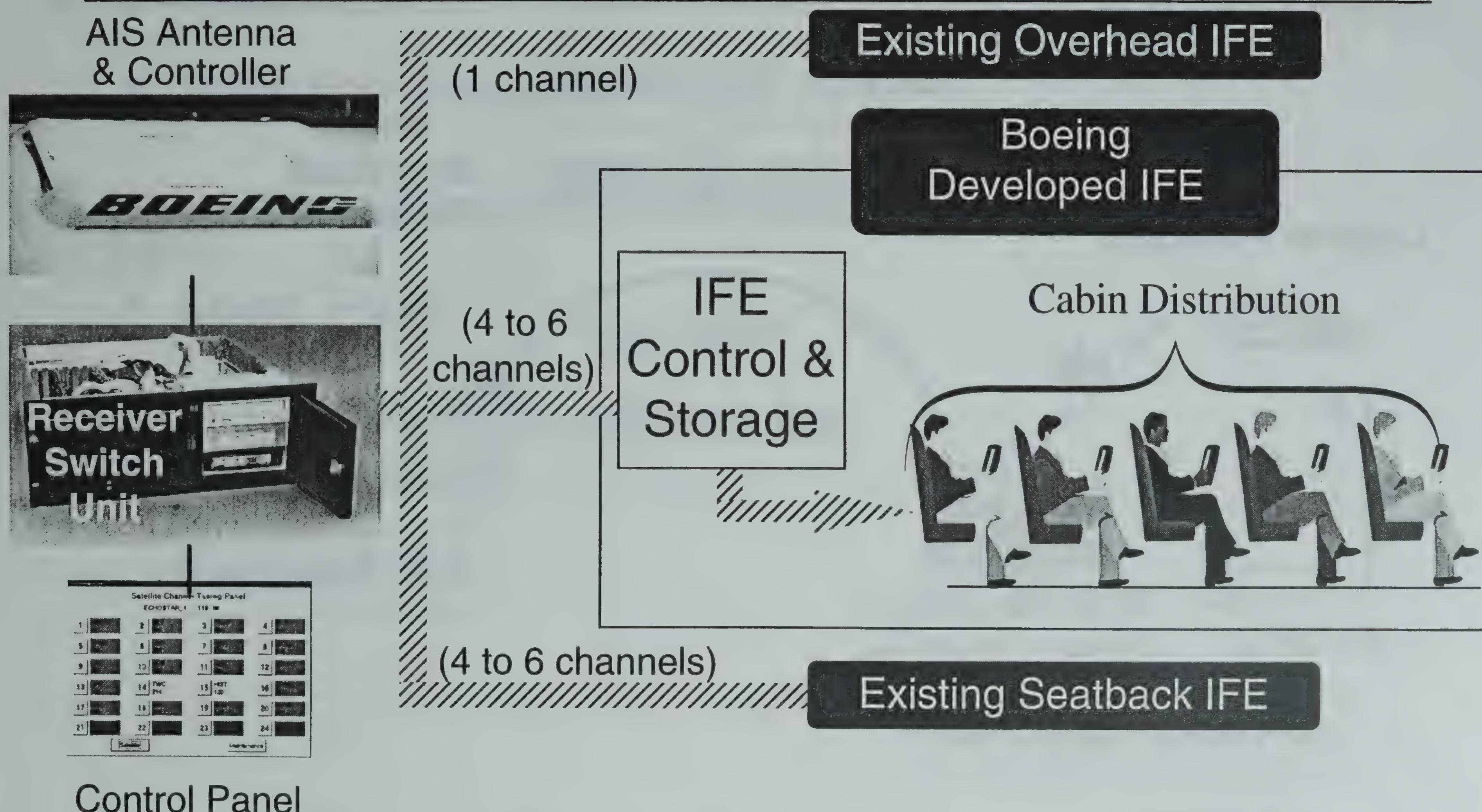
8E- 3 System Diagram



Aviation Information Services

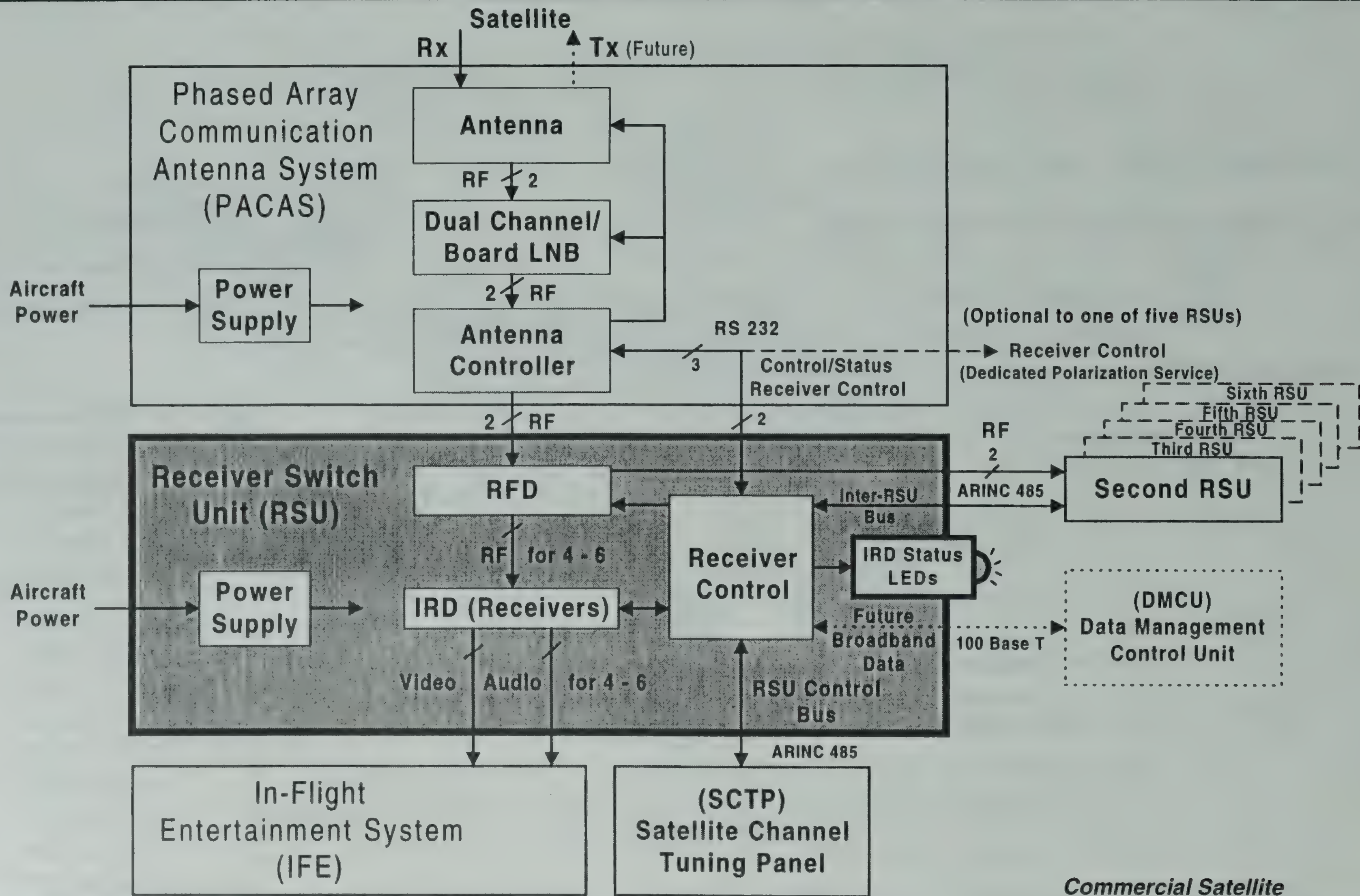
Near-Term Airplane Architecture

8E- 4



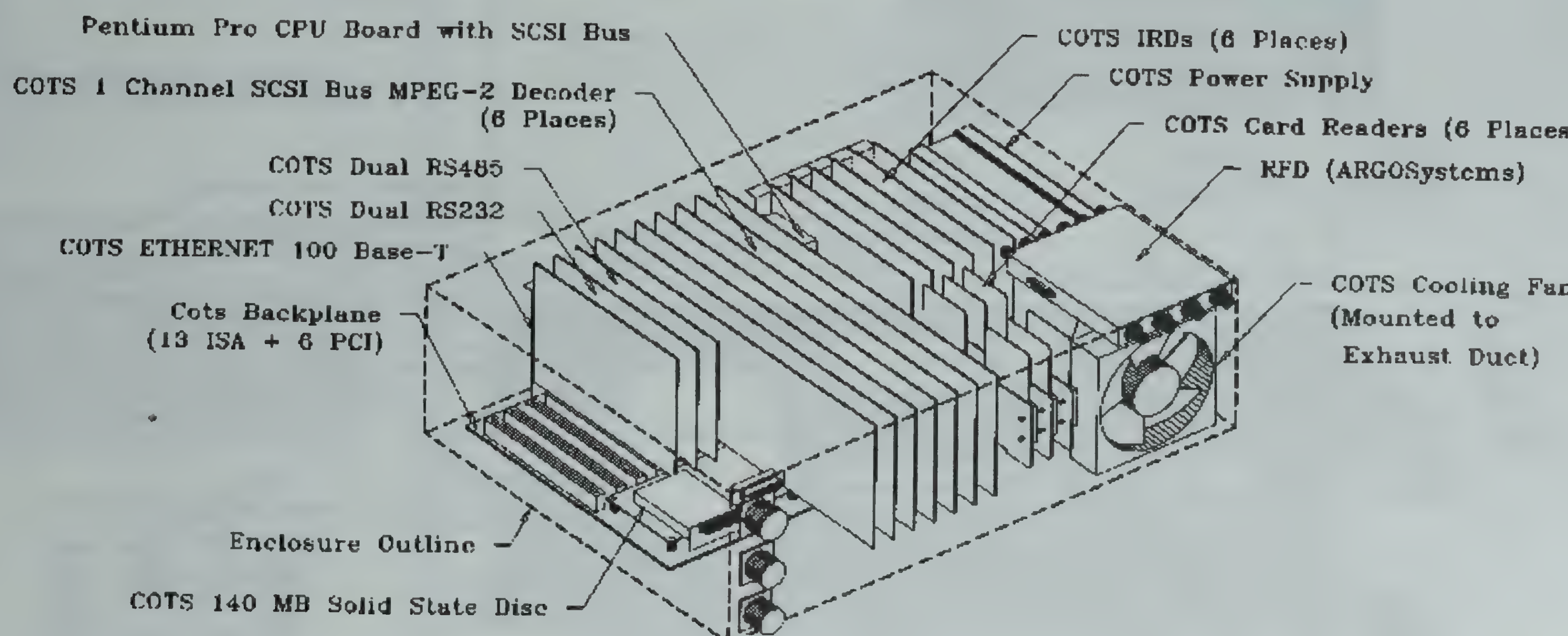
Aviation Information Services

8E- 5 Airplane Block Diagram



Aviation Information Services

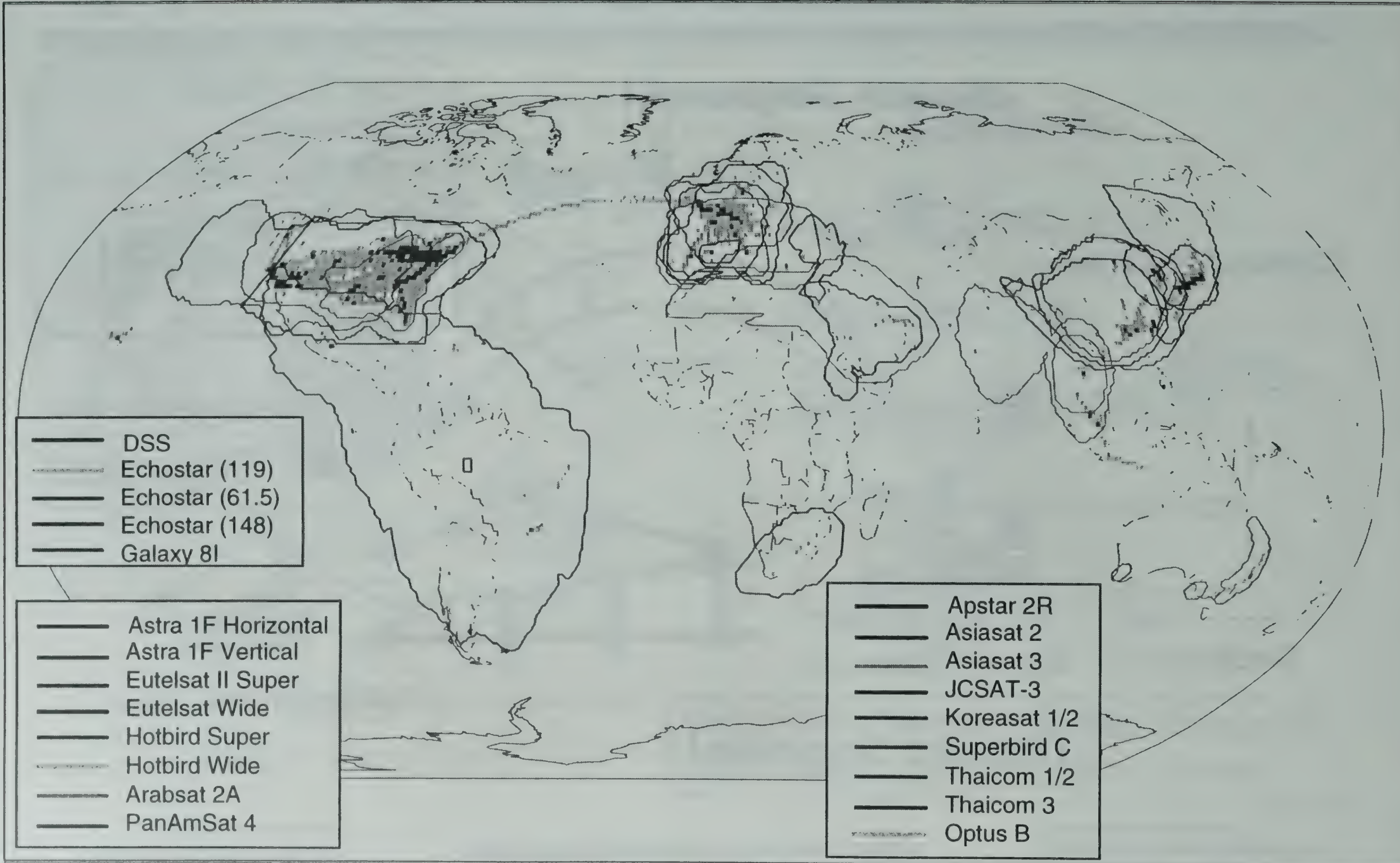
8E- 6 Receiver Switch Unit



BOEING AiS

Aviation Information Services

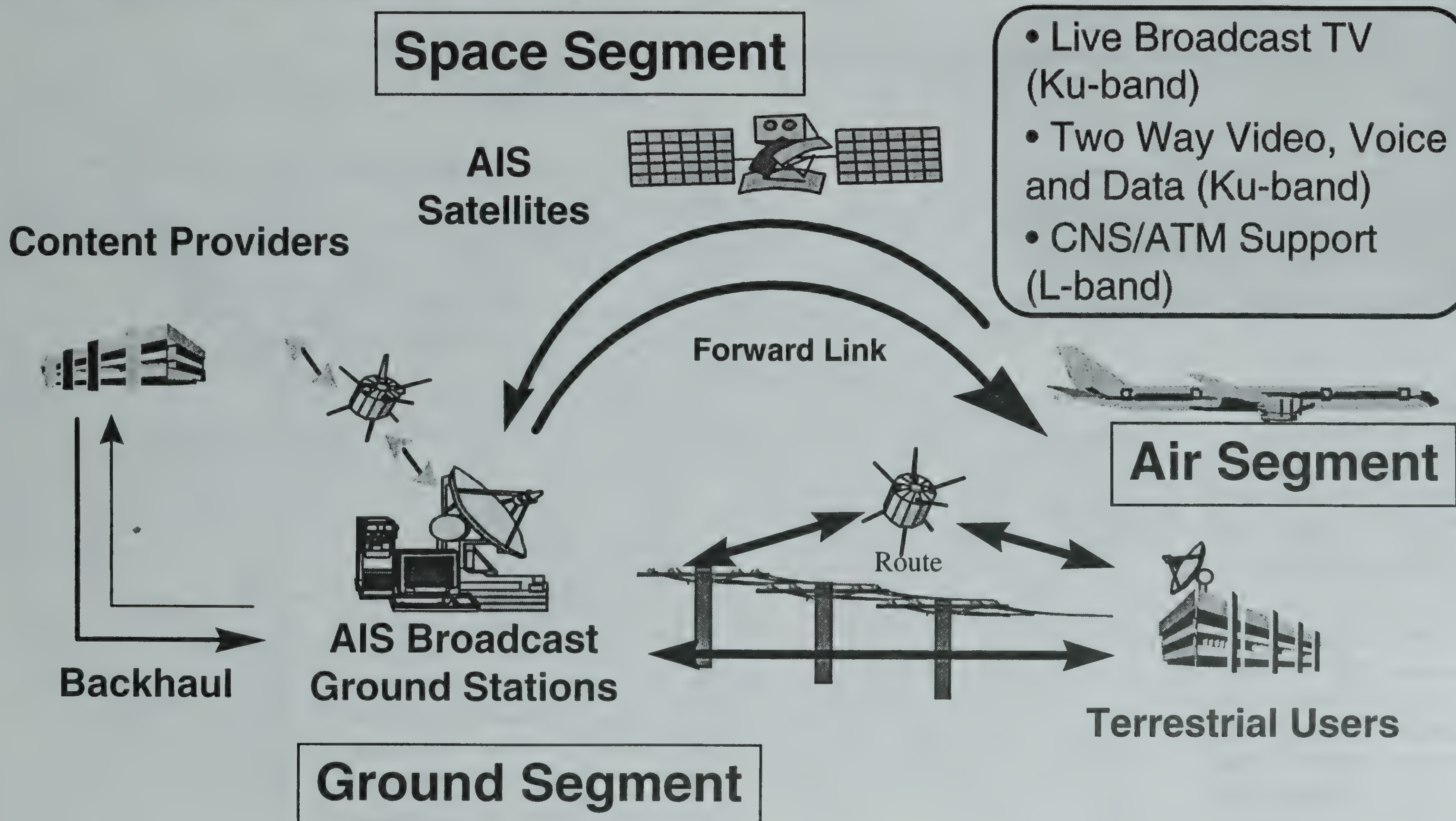
Air Traffic Flow/DBS Satellite Coverage



Aviation Information Services

Long-Term System Diagram

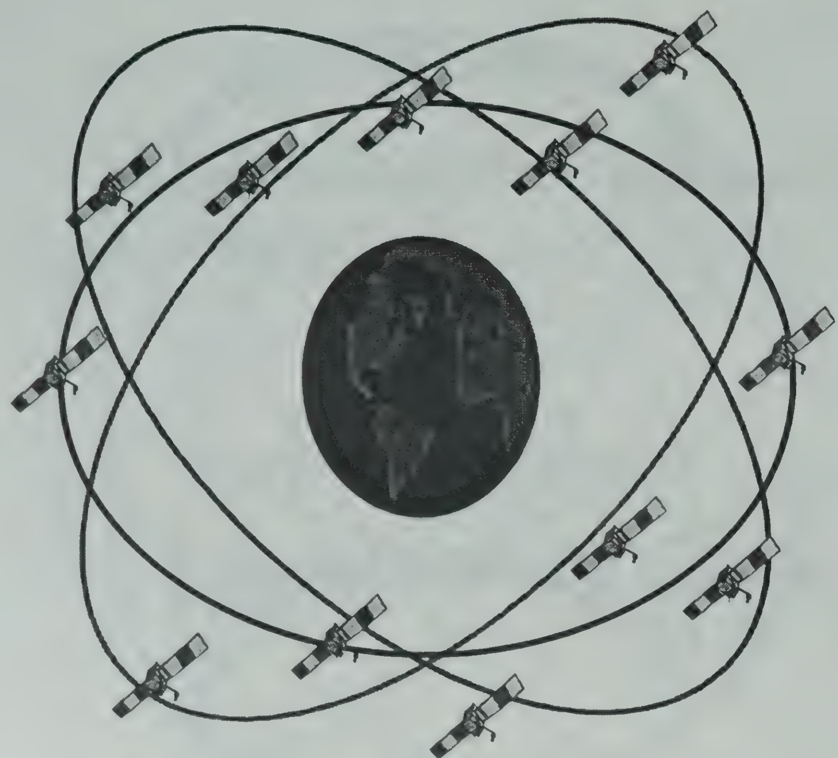
8E- 8



Aviation Information Services

8E- 9

AIS Constellation



MEO

Medium Earth Orbit

Features

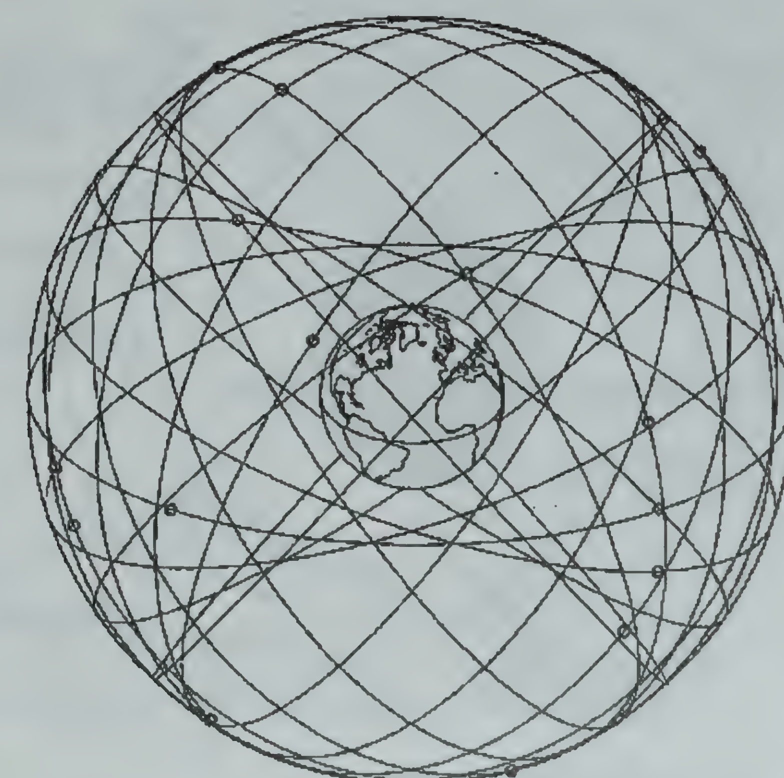
- **Global coverage**
- **High latitudes**
- **Supports CNS/ATM**
- **Limited interference**
- **Limited handoffs**

CNS/ATM - Communications, Navigation, Surveillance/ Air Traffic Management

Aviation Information Services

8E- 10 AIS Constellation

- 16 satellites
  - 16 planes
  - 1 satellite/plane
- 10,900 nm altitude
- 53° inclination
- 11.96 hour period
- Visibility
  - 209.11 min at 25° elevation

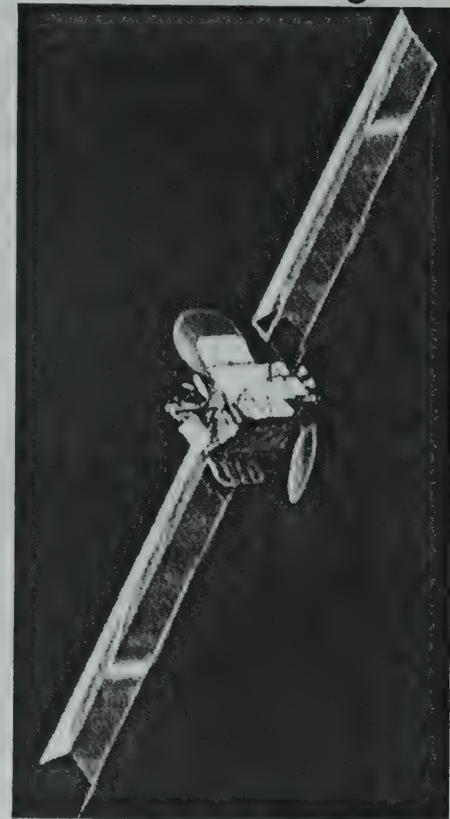


Aviation Information Services

8E- 11 AIS Constellation

- ~ 12.5 kW power
- 3-axis stabilized sun-nadir pointed
- Ku-band payload
- 12+ year design life
- L-band CNS/ATM payload

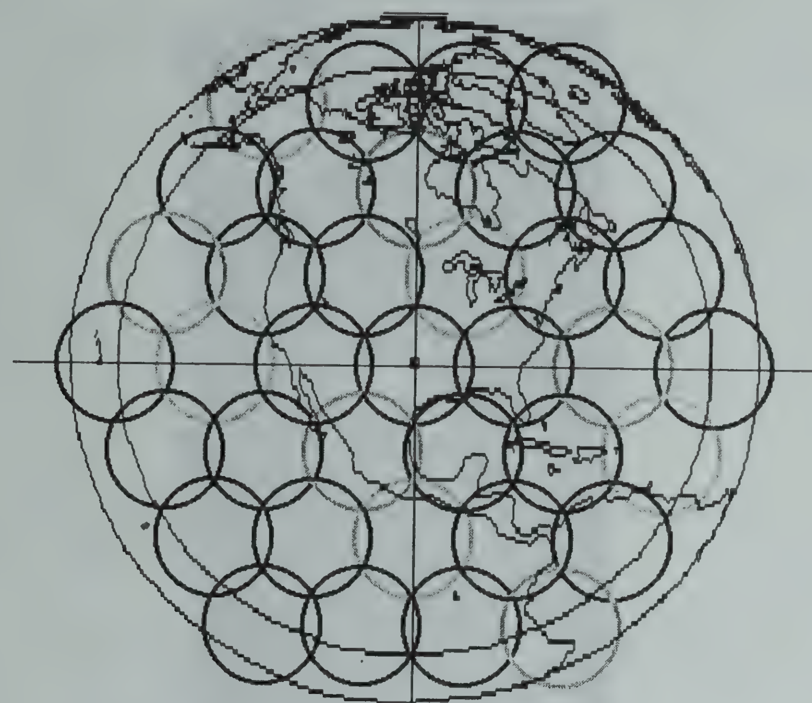
Sample
Satellite Design



Hughes HS-702

Aviation Information Services

8E- 12 Downlink Beams

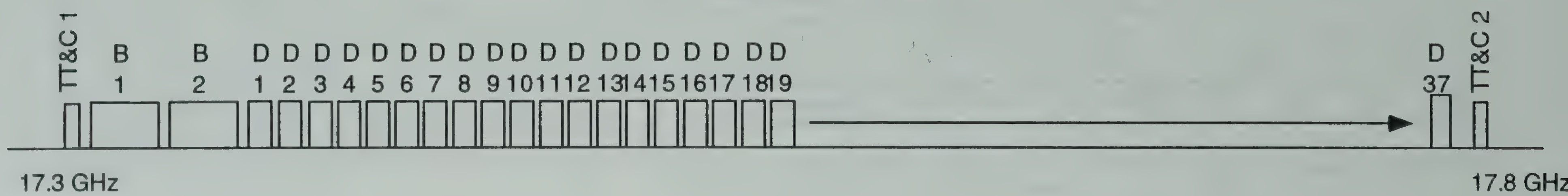


- 500*2 MHz total bandwidth
- 7-cell reuse pattern
- 37 cells
- 5.28 frequency reuse
- 68.18 MHz per cell

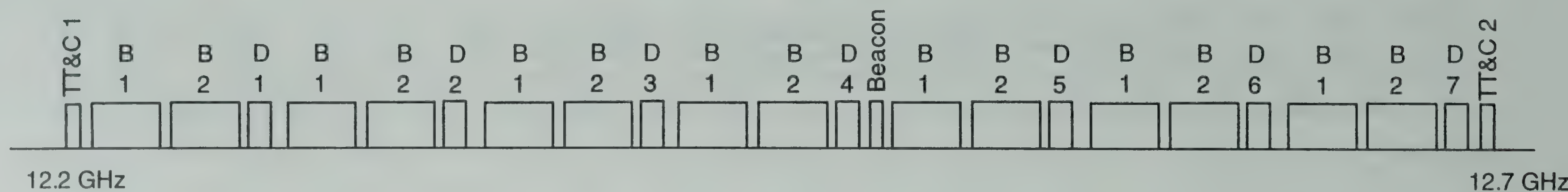
Aviation Information Services

8E- 13 Forward Link Frequency Plan

Forward Uplink Plan

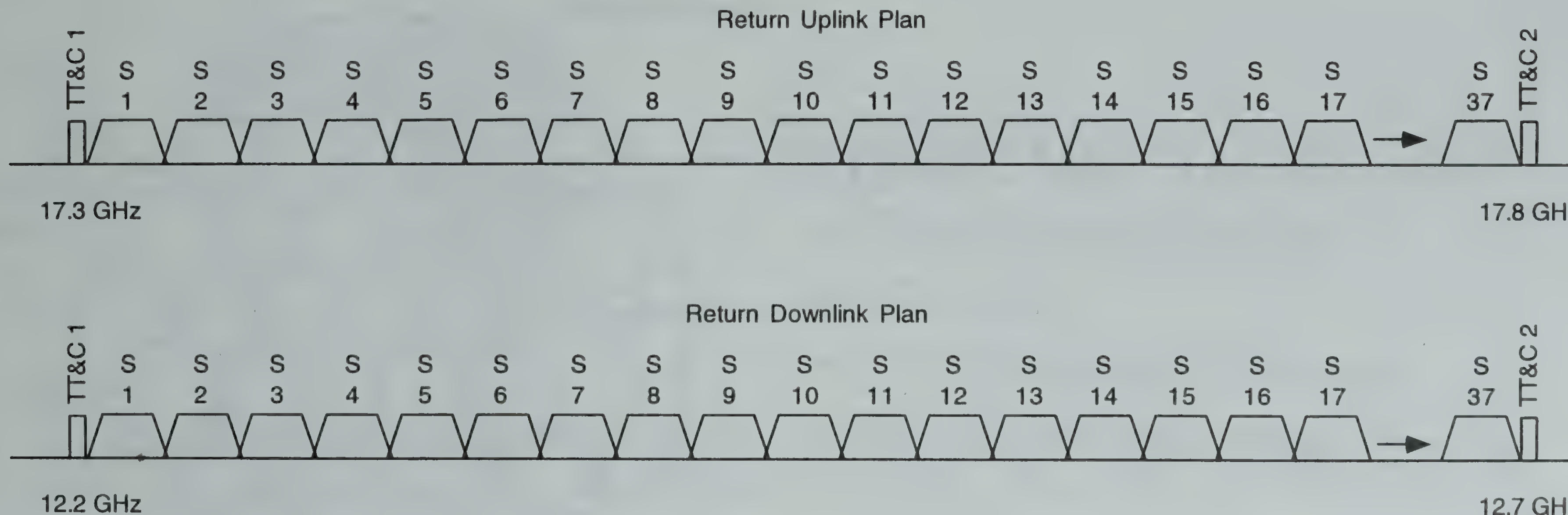


Forward Downlink Plan



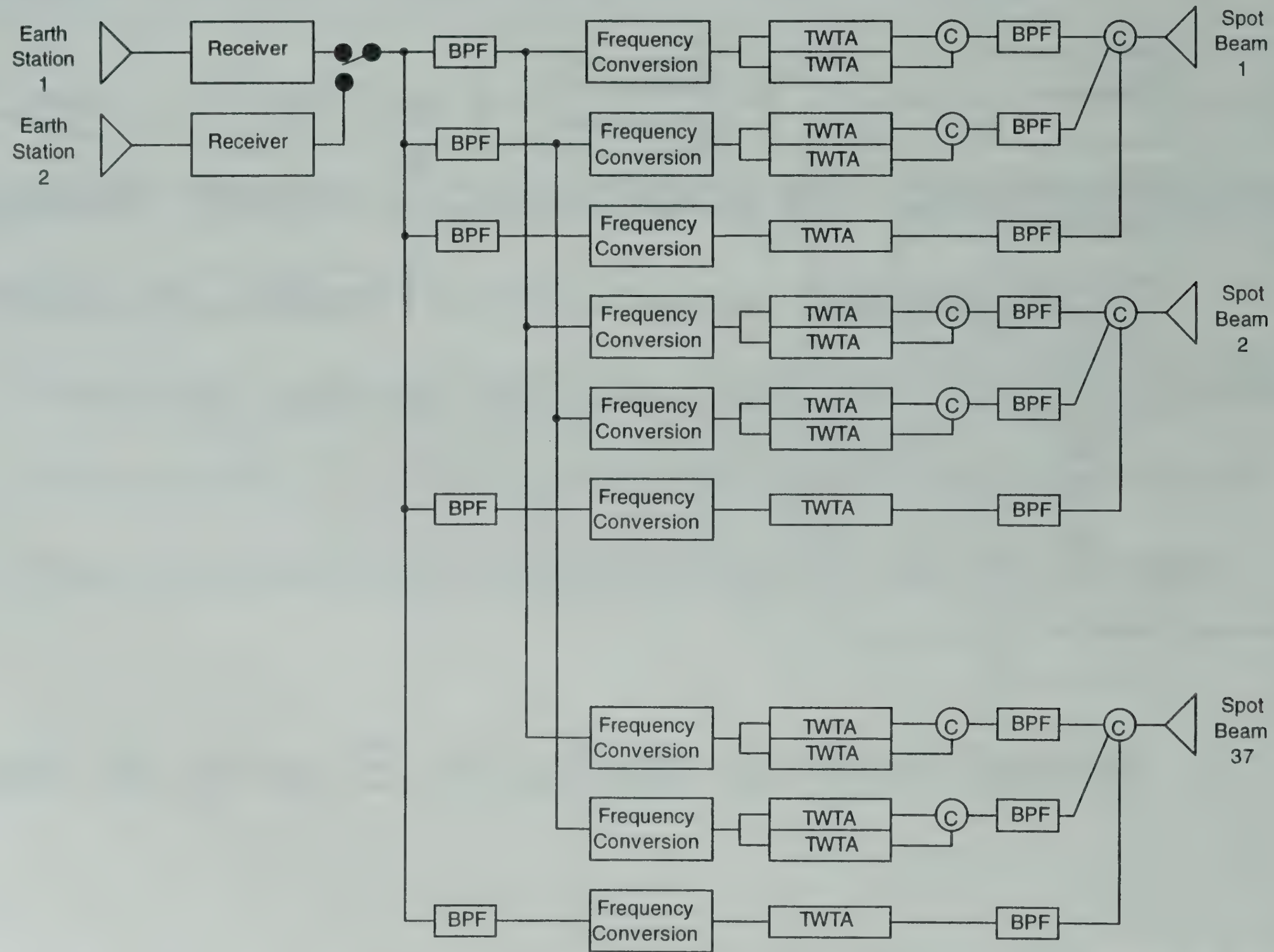
Aviation Information Services

8E- 14 Return Link Frequency Plan



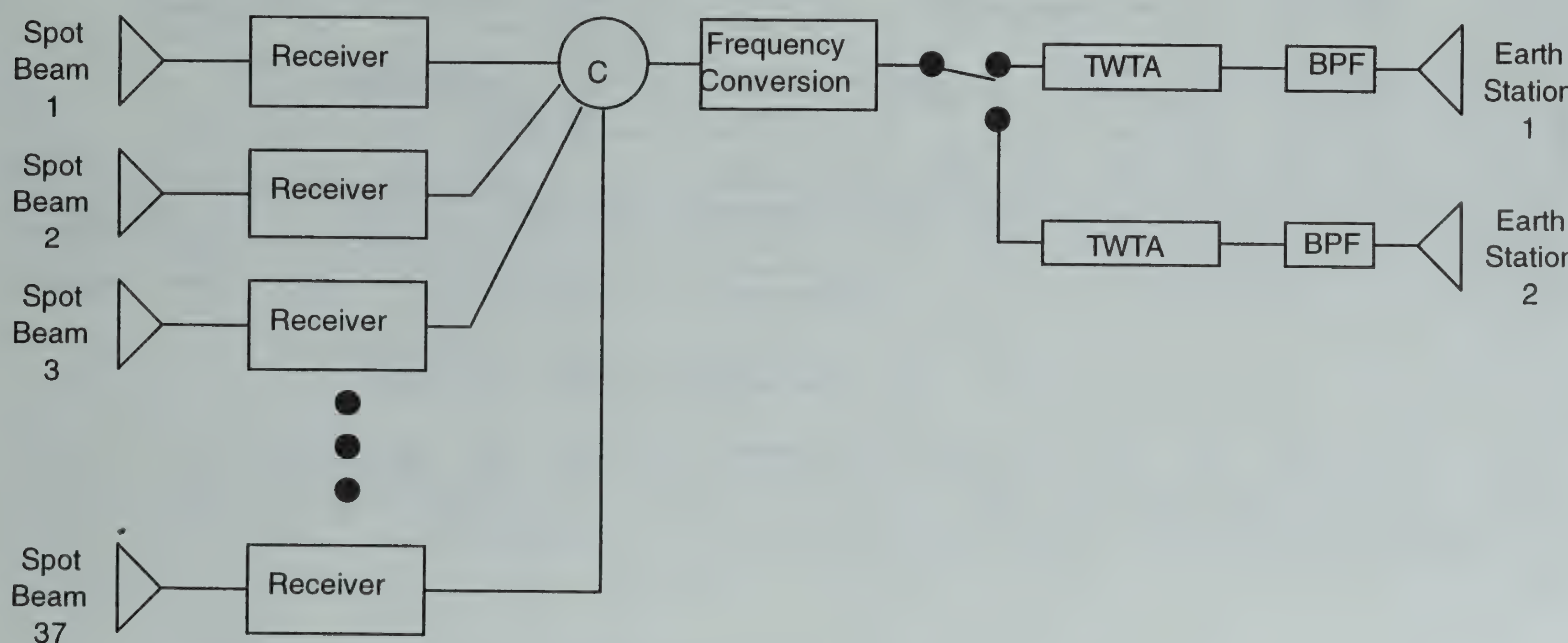
Aviation Information Services

8E- 15 Forward Link Communications Payload



Aviation Information Services

8E- 16 Return Link Communications Payload



Complete a Course Evaluation

8E- 17

Answer these 4 questions on back of form:

12. What *did you get* from the course *that was good*?

13. What *didn't you get that you expected* from the course?

14. What would you *like to have in-hand* when you leave?

15. What *changes/improvements* would you like to see?

Hand in your Evaluation as you leave.

Notes

8E- 18

Contents

References

Reference 1	A Structured Overview of Digital Communications "A Tutorial Review"
Reference 2	Guide for Metric Practice
Reference 3	Telecommunications for the 21st Century
Reference 4	The Orbiting Internet "Fiber in the Sky"
Reference 5a	Engineering Issues & Design Choices (Comparison - TDMA, FDMA)
Reference 5b	Engineering Issues & Design Choices (Comparison - TDMA, FDM, CDMA)
Reference 5c	Physics of Satellite Communications (RF Basics - Frequency Spectrum)
Reference 5d	Physics of Satellite Communications (RF Basics - Frequency Bands)
Reference 6	Chart - Commercial Supercomputer Products
Reference 7	Defense Department Constructs Global Communications Network
Reference 8	Symbols and Acronyms

Commercial Satellite Communication Applications

Course No. 9SV109

Reference 1

A Structured Overview of Digital Communications "A Tutorial Review"

A Structured Overview of Digital Communications—a Tutorial Review—Part I

8/1983

BERNARD SKLAR

Part I of a two-part overview of digital communications.

AN IMPRESSIVE assortment of communications signal processing techniques has arisen during the past two decades. This two-part paper presents an overview of some of these techniques, particularly as they relate to digital satellite communications. The material is developed in the context of a structure used to trace the processing steps from the information source to the information sink. Transformations are organized according to functional classes: formatting and source coding, modulation, channel coding, multiplexing and multiple access, frequency spreading, encryption, and synchronization. The paper begins by treating formatting, source coding, modulation, and potential trade-offs for power-limited systems and bandwidth-limited systems.

Communications via satellites have two unique characteristics: the ability to cover the globe with a flexibility that cannot be duplicated with terrestrial links, and the availability of bandwidth exceeding anything previously available for intercontinental communications [1]. Most satellite communications systems to date have been analog in nature. However, digital communications is becoming increasingly attractive because of the ever-growing demand for data communication, and because digital transmission offers data processing options and flexibilities not available with analog transmission [2].

This paper presents an overview of digital communications in general; for the most part, however, the treatment is in the context of a satellite communications link. The key feature of a digital communications system (DCS) is that it sends only a finite set of messages, in contrast to an analog communications system, which can send an infinite set of messages. In a DCS, the objective at the receiver is not to reproduce a waveform with precision; it is instead to determine from a noise-perturbed signal which of the finite set of waveforms had been sent by the transmitter. An important measure of system performance is the average number of erroneous decisions made, or the probability of error (P_E).

Figure 1 illustrates a typical DCS. Let there be M symbols or messages $m_1, m_2, \ldots, m_M$ to be transmitted. Let each symbol be represented by transmitting a corresponding waveform $s_1(t), s_2(t), \ldots, s_M(t)$. The symbol (or message) m_i is sent by transmitting the digital waveform $s_i(t)$ for T seconds, the symbol period. The next symbol is sent over the next period. Since the M symbols can be represented by $k = \log_2 M$ binary digits (bits), the data rate can be expressed as

$$R = (1/T)\log_2 M = k/T \text{ b/s}.$$

Data rate is usually expressed in bits per second (b/s) whether or not binary digits are actually involved. A binary symbol is the special case characterized by $M = 2$ and $k = 1$. A digital waveform is taken to mean a voltage or current waveform representing a digital symbol. The waveform is endowed with specially chosen amplitude, frequency, or phase characteristics that allow the selection of a distinct waveform for each symbol from a finite set of symbols. At various points along the signal route, noise corrupts the waveforms $s(t)$ so that its reception must be termed an estimate $\hat{s}(t)$. Such noise, and its deleterious effect on system performance, will be treated in Part II of this paper, which will appear in the October 1983 *IEEE Communications Magazine*.

Signal Processing Steps

The functional block diagram shown in Fig. 1 illustrates the data flow through the DCS. The upper blocks, which are labeled *format*, *source encode*, *encrypt*, *channel encode*, *multiplex*, *modulate*, *frequency spread*, and *multiple access*, dictate the signal transformations from the source to the transmitter. The lower blocks dictate the signal transformations from the receiver back to the source; the lower blocks essentially reverse the signal processing steps performed by the upper blocks. The blocks within the dashed lines initially consisted only of the modulator and demodulator functions, hence the name MODEM. During the past two decades, other signal processing functions were frequently incorporated within the same assembly as the modulator and demodulator. Consequently, the term MODEM often encompasses the processing steps shown within the dashed lines of Fig. 1. When this is the case, the MODEM can be thought of as the

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"brains" of the system, and the transmitter and receiver as the "muscles." While the transmitter consists of a frequency up-conversion stage, a high-power amplifier, and an antenna, the receiver portion is occupied by an antenna, a low-noise front-end amplifier, and a down-converter stage, typically to an intermediate frequency (IF).

Of all the signal processing steps, only formatting, modulation, and demodulation are essential for all DCS's; the other processing steps within the MODEM are considered design options for various system needs. Source encoding, as defined here, removes information redundancy and performs analog-to-digital (A/D) conversion. Encryption prevents unauthorized users from understanding messages and from injecting false messages into the system. Channel coding can, for a given data rate, improve the P_E performance at the expense of power or bandwidth, reduce the system bandwidth requirement at the expense of power or P_E performance, or reduce the power requirement at the expense of bandwidth or P_E performance. Frequency spreading renders the signal less vulnerable to interference (both natural and intentional) and can be used to afford privacy to the communicators. Multiplexing and multiple access combine signals that might have different characteristics or originate from different sources.

The flow of the signal processing steps shown in Fig. 1 represents a typical arrangement; however, the blocks are sometimes implemented in a different order. For example, multiplexing can take place prior to channel encoding, prior to modulation, or—with a two-step modulation process (subcarrier and carrier)—it can be performed between the two steps. Similarly, spreading can take place anywhere along the transmission chain; its precise location depends on the particular technique used. Figure 1 illustrates the reciprocal aspect of the procedure; any signal processing steps which take place in the transmitting chain must be reversed in the receiving chain. The figure also indicates that, from the source to the modulator, a message takes the form of a bit stream, also called a baseband signal. After modulation, the message takes the form of a digitally encoded sinusoid (digital waveform). Similarly, in the reverse direction, a received message appears as a digital waveform until it is demodulated. Thereafter it takes the form of a bit stream for all further signal processing steps.

Figure 2 shows the basic signal processing functions, which may be viewed as transformations from one signal space to another. The transformations are classified into seven basic groups:

- formatting and source coding
- modulation
- channel coding
- multiplexing and multiple access
- spreading
- encryption
- synchronization

The organization has some inherent overlap, but nevertheless provides a useful structure for this overview. The text by

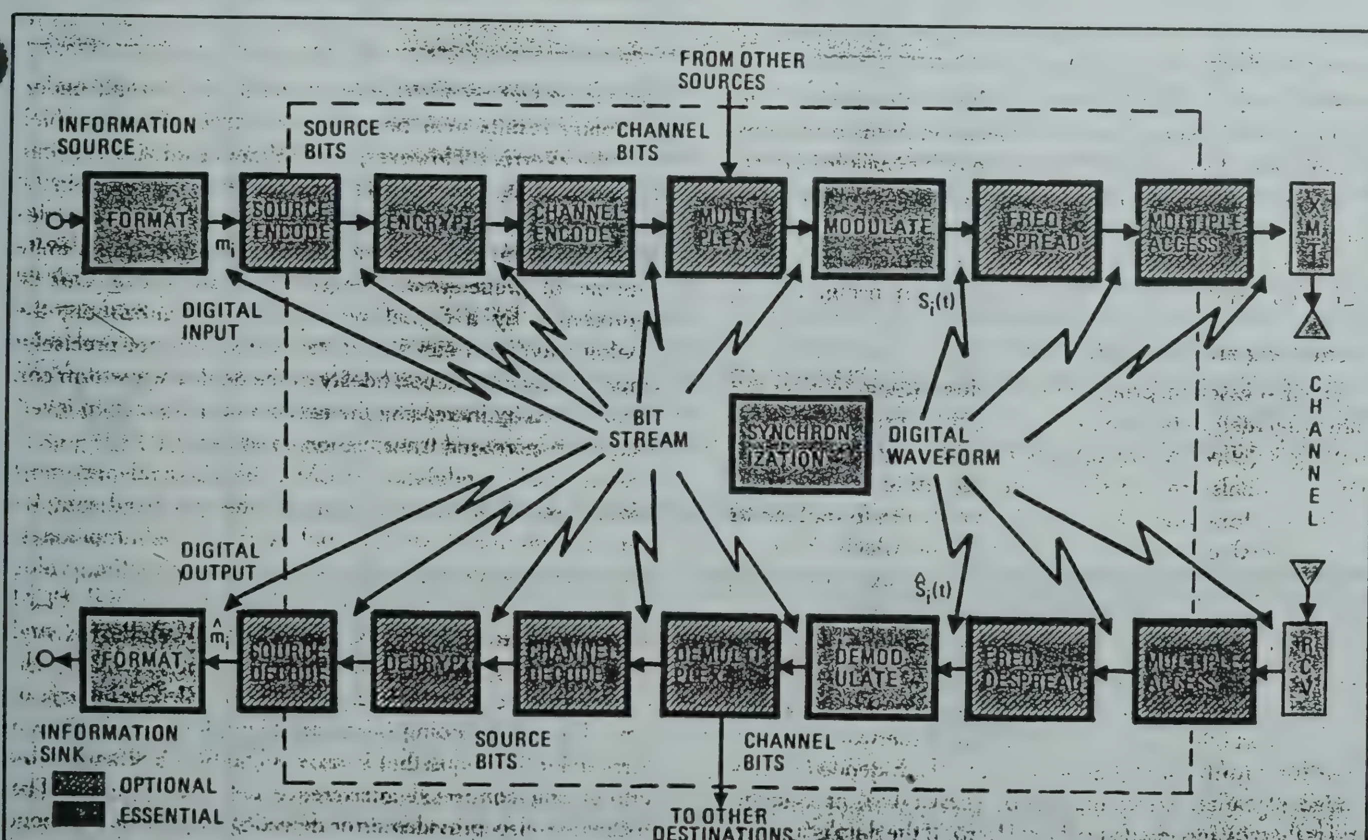


Fig. 1. Block diagram of a typical digital communication system.

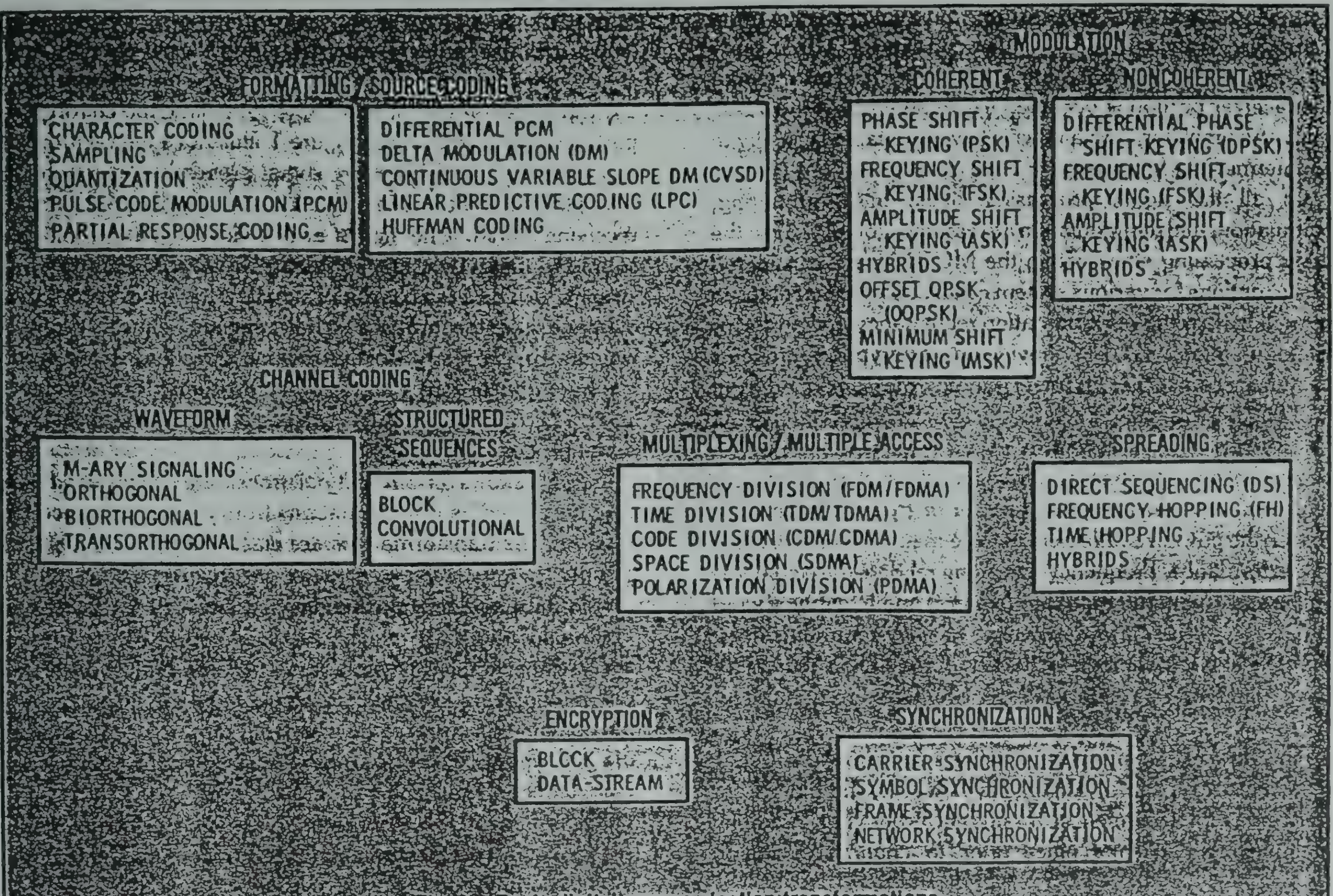


Fig. 2. Basic digital communication transformations.

Lindsey and Simon [3] is an excellent reference for the modulation, coding, and synchronization transformations treated here. The comprehensive books by Spilker [4] and Bhargava et al. [5] specifically address digital communications by satellite. The seven basic transformations will now be treated individually, in the general order of their importance rather than in the order of the blocks shown in Fig. 1.

Formatting and Source Coding

The first essential processing step, formatting, renders the communicated data compatible for digital processing. Formatting is defined as any operation that transforms data into digital symbols. Source coding means data compression in addition to formatting. Some authors consider formatting to be a special case of source coding (for which the data compression amounts to zero), instead of making a distinction between the two. The source of most communicated data (except for computer-to-computer transmissions already in digital form) is either textual or analog in nature. If the data consists of alphanumeric text, it is character-encoded with one of several standard formats, such as American Standard Code for Information Interchange (ASCII), Extended Binary Coded Decimal Interchange Code (EBCDIC), or Baudot, and is thereby rendered into digital form. If the data is analog, the (band-limited) waveform must first be sampled at a rate of at least $2f_m$ Hz (the Nyquist frequency), where f_m is the highest frequency contained in the waveform. Such sampling insures perfect reconstruction of the analog signal; undersampling results in a phenomenon called aliasing, which introduces errors. However, the minimum sampling rate can be less than $2f_m$ if the lowest signal frequency contained in the waveform is nonzero [6]. Quantization of the time samples allows each sample to be expressed as a level from a finite number of predetermined levels; each such level can be represented by a digital symbol. After quantization, the analog waveform can still be recovered, but not precisely; improved reconstruction fidelity of the analog waveform can be achieved by increasing the number of quantization levels (requiring increased transmission bandwidth).

Pulse code modulation (PCM), the classical and most widely used digital format, converts the quantized samples into code groups of two-level pulses using fixed amplitudes. Each pulse group represents a quantized amplitude value expressed in binary notation. There are several PCM subformats (such as nonreturn to zero, Manchester, and Miller), each providing some special feature, such as self-clocking or a compact spectral signature [3]. Duobinary, or partial response coding (also called correlative coding), is a formatting technique that improves bandwidth efficiency by introducing controlled interference between symbols. The technique also provides error-detecting capabilities without introducing redundancy into the data stream [7-9].

Both source encoding and formatting mean encoding the source data with a digital format (A/D conversion); in this

sense alone, the two are identical. However, the term "source encoding" has taken on additional meaning in DCS usage. Besides digital formatting, "source encoding" has also come to denote data compression (or data rate reduction). With standard A/D conversion using PCM, data compression can only be achieved by lowering the sampling rate or reducing the number of quantization levels per sample, each of which increases the mean squared error of the reconstructed signal. Source encoding techniques accomplish rate reduction by removing the redundancy that is indigenous to most message transmissions, without sacrificing reconstruction fidelity. A digital data source is said to possess redundancy if the symbols are not equally likely or if they are not statistically independent. Source encoding can reduce the data rate if either of these conditions exists. A few descriptions of common source coding techniques follow.

Differential PCM (DPCM) utilizes the differences between samples rather than their actual amplitude. For most data, the average amplitude variation from sample to sample is much less than the total amplitude variation; therefore, fewer bits are needed to describe the difference. DPCM systems actually encode the difference between a current amplitude sample and a predicted amplitude value estimated from past samples. The decoder utilizes a similar algorithm for decoding. Delta modulation (DM) is the name given to the special case of DPCM where the quantization level of the output is taken to be one bit. Although DM can be easily implemented, it suffers from "slope overload," a condition in which the incoming signal slope exceeds the system's capability to follow the analog source closely at the given sampling rate. To improve performance whenever slope overload is detected, the gain of the system can be varied according to a predetermined algorithm known to the receiver. If the system is designed to adaptively vary the gain over a continuous range, the modulation is termed continuous variable slope delta (CVSD) modulation, or adaptive delta modulation (ADM). Speech coding of good quality has been demonstrated with CVSD at bit rates less than 25 kb/s, a notable data rate reduction when compared with the 56-kb/s PCM used with commercial telephone systems [10].

Another example of source coding is linear predictive coding (LPC). This technique is useful where the waveform results from a process that can be modeled as a linear system. Rather than encode samples of the waveform, significant features of the process are encoded. For speech, these include gain, pitch, and voiced or unvoiced information. Whereas in PCM each sample is processed independently, a predictive system such as DPCM uses a weighted sum of the n-past samples to predict each present sample; it then transmits the "error" signal. The weights are calculated to minimize the average energy in the error signal that represents the difference between the predicted and actual amplitude. For speech, the weights are calculated over short waveform segments of 10 to 30 ms, and thus change as the speech statistics vary. The LPC technique has been used to produce acceptable speech quality at a data rate of 2.4 kb/s, and high quality at 7.2 kb/s [11-13]. For current perspectives in digital formatting of speech, see Crochiere and Flanagan [14].

Some source coding techniques employ code sequences of unequal length so as to minimize the average number of bits required per data sample. A useful coding procedure, called Huffman coding [15,16], can be used for effecting data compression upon any symbol set, provided the *a priori* probability of symbol occurrence is known and not equally likely. Huffman coding generates a binary sequence for each symbol so as to achieve the smallest average number of bits per sample, for the given *a priori* probabilities. The technique involves assigning shorter code sequences to the symbols of higher probability, and longer code sequences to those of lower probability. The price paid for achieving data rate reduction in this way is a commensurate increase in decoder complexity. In addition, there is a tendency for symbol errors, once made, to propagate for several symbol periods.

Digital Modulation Formats

Modulation, in general, is the process by which some characteristic of a waveform is varied in accordance with another waveform. A sinusoid has just three features which can be used to distinguish it from other sinusoids—phase, frequency, and amplitude. For the purpose of radio transmission, modulation is defined as the process whereby the phase, frequency, or amplitude of a radio frequency (RF) carrier wave is varied in accordance with the information to be transmitted. Figure 3 illustrates examples of digital modulation formats: phase shift keying (PSK), frequency shift keying (FSK), amplitude shift keying (ASK), and a hybrid combination of ASK and PSK sometimes called quadrature amplitude modulation (QAM). The first column lists the analytic expression, the second is a pictorial of the waveform, and the third is a vectorial picture. In the general M-ary signaling case, the processor accepts k source bits at a time, and instructs the modulator to produce one of an

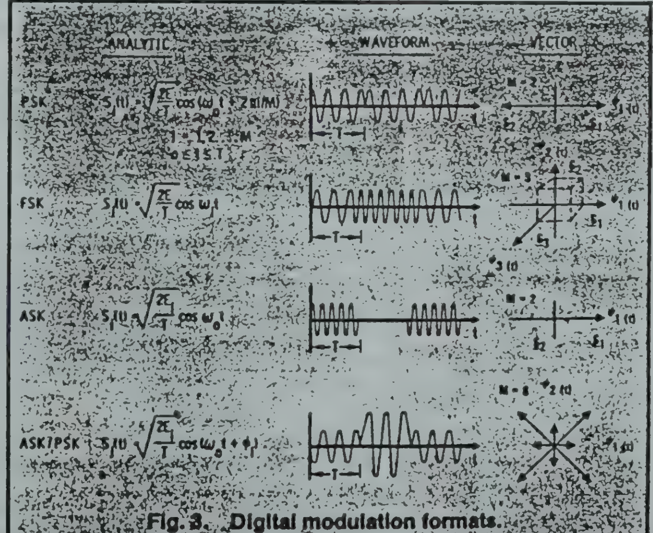


Fig. 3. Digital modulation formats.

available set of $M = 2^k$ waveform types. Binary modulation, where $k = 1$, is just a special case of M-ary modulation. For the binary PSK (BPSK) example in Fig. 3, M is equal to two waveform types (2-ary). For the FSK example, M is equal to three waveform types (3-ary); note that this $M = 3$ choice for FSK has been chosen to emphasize the mutually perpendicular axes. In practice, M is usually a nonzero power of two (2,4,8,16,...). For the ASK example, M equals two waveform types; for the ASK/PSK example, M equals eight waveform types (8-ary). The vectorial picture for each modulation type (except FSK) is characterized on a plane whose polar coordinates represent signal amplitude and phase. Signal sets that can be depicted with opposing vectors (phase difference equals 180°) on such a plane, for example BPSK, are called antipodal signals. In the case of FSK modulation, the vectorial picture is characterized by cartesian coordinates, such that each of the mutually perpendicular axes represents a different transmission frequency. Signal sets that can be characterized with such orthogonal axes are called orthogonal signals.

Modulation was defined as that process wherein a carrier or subcarrier waveform is varied by a baseband signal; the hierarchy for digital modulation is shown in Fig. 2. When the receiver exploits knowledge of the carrier wave's phase reference to detect the signals, the process is called coherent detection; when it does not have phase reference information, the process is called noncoherent. In ideal coherent detection, prototypes of the possible arriving signals are available at the receiver. These prototype waveforms exactly replicate the signal set in every respect, even RF phase. The receiver is then said to be phase-locked to the transmitter. During detection, the receiver multiplies and integrates (correlates) the incoming signal with each of its prototype replicas. Under the heading of coherent modulaton (see Fig. 2) PSK, FSK, and ASK are listed, as well as hybrid combinations.

Noncoherent modulation refers to systems designed to operate with no knowledge of phase; phase estimation processing is not required. Reduced complexity is the advantage over coherent systems, and increased P_E is the trade-off. Figure 2 shows that the modulation types listed in the noncoherent column almost identically replicate those in the coherent column. The only difference is that there cannot be "noncoherent PSK" because noncoherent means without using phase information. However, there is a "pseudo PSK" technique termed differential PSK (DPSK) that utilizes RF phase information of the prior symbol as a phase reference for detecting the current symbol (described in the section titled "Demodulation").

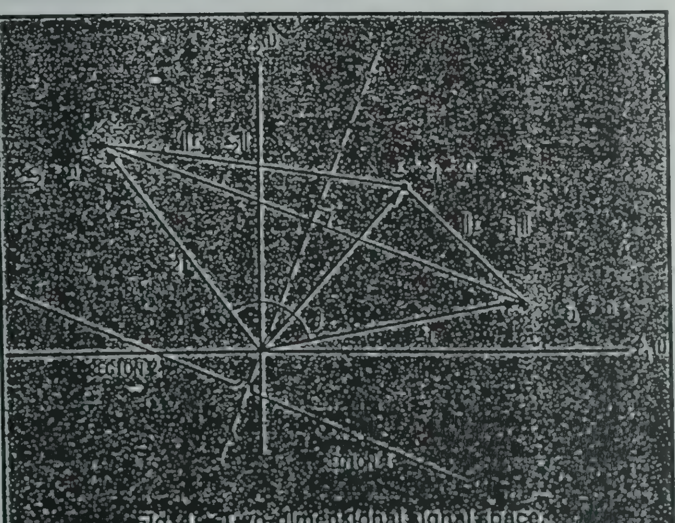


Fig. 4. Two-dimensional signal space.

Two digital modulation schemes of special interest for use on nonlinear bandlimited channels are called staggered (or offset) quadraphase PSK (SQPSK or OQPSK), and minimum shift keying (MSK). Both techniques retain low-spectral sidelobe levels while allowing efficient detection performance. The generation of both can be represented as two orthogonal, antipodal binary systems with the symbol timing in the two channels offset by one-half of a symbol duration. OQPSK uses rectangular pulse shapes, and MSK uses half-cycle sinusoid pulse shapes. Because of the sinusoidal pulse shaping in MSK, it can be viewed as continuous-phase FSK with a frequency deviation equal to one-half the bit rate [17,18].

Demodulation

The analysis of all coherent demodulation or detection schemes involves the concept of distance between an unknown received waveform and a set of known waveforms. Euclidean-like distance measurements are easily formulated in a signal space described by mutually perpendicular axes. It can be shown [19] that any arbitrary finite set of waveforms $s_i(t)$, where $s_i(t)$ is physically realizable and of duration T, can be expressed as a linear combination of N orthonormal waveforms $\phi_1(t), \phi_2(t), \ldots, \phi_N(t)$, such that

$$s_i(t) = \sum_{j=1}^{N} a_{ij}\, \phi_j(t) \tag{1}$$

where

$$a_{ij} = \int_0^T s_i(t)\, \phi_j(t)\, dt \qquad \begin{array}{l} i = 1,2,\ldots,M \\ j = 1,2,\ldots,N \\ N \leq M \end{array} \qquad 0 \leq t \leq T \tag{2}$$

and

$$\int_0^T \phi_i(t)\, \phi_j(t)\, dt = \begin{cases} 1 & (\text{for } i = j) \\ 0 & (\text{otherwise}) \end{cases} \tag{3}$$

Additive white Gaussian noise (AWGN) can similarly be expressed as a linear combination of orthonormal waveforms

$$n(t) = \sum_{j=1}^{N} n_j\, \phi_j(t) + \tilde{n}(t)$$

where

$$n_j = \int_0^T n(t)\, \phi_j(t)\, dt \tag{4}$$

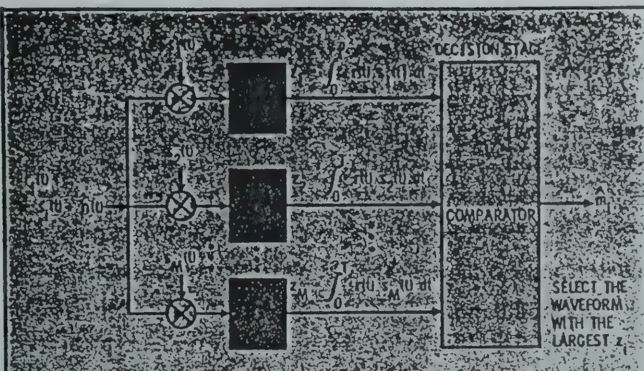


Fig. 5. Product integrators (correlators) and decision stage.

For the signal detection problem, the noise can be partitioned into two components

$$n(t) = \hat{n}(t) + \tilde{n}(t)$$

where

$$\hat{n}(t) = \sum_{j=1}^{N} n_j \, \phi_j(t) \qquad (5)$$

is taken to be the noise within the signal space, or the projection of the noise components on the signal axes $\phi_1(t)$, $\phi_2(t)$, ... , $\phi_N(t)$, and

$$\tilde{n}(t) = n(t) - \hat{n}(t)$$

is defined as the noise outside the signal space. In other words, $\tilde{n}(t)$ may be thought of as the noise that is effectively tuned out by the detector. The symbol $\hat{n}(t)$ represents the noise that will interfere with the detection process, and it will henceforth be referred to simply as $n(t)$. Once a convenient set of N orthonormal functions has been adopted (note that $\phi(t)$ is not constrained to any specific form), each of the transmitted signal waveforms $s_i(t)$ is completely determined by the vector of its coefficients

$$\boldsymbol{s}_i = (a_{i1}, a_{i2}, \ldots, a_{iN}) \qquad i = 1, 2, \ldots, M$$

Similarly, the noise $n(t)$ can be expressed by the vector of its coefficients

$$\boldsymbol{n} = (n_1, n_2, \ldots, n_N)$$

where $\boldsymbol{n}$ is a random vector with zero mean and Gaussian distribution.

Since *any* arbitrary waveform set, as well as noise, can be represented as a linear combination of orthonormal waveforms (see (1)-(5)), we are justified in using (Euclidean-like) distance in such an orthonormal space, as a decision criterion for the detection of *any* signal set in the presence of AWGN.

Detection in the Presence of AWGN

Figure 4 illustrates a two-dimensional signal space, the locus of two noise-perturbed prototype binary signals ($\boldsymbol{s}_1 + \boldsymbol{n}$) and ($\boldsymbol{s}_2 + \boldsymbol{n}$), and a received signal $\boldsymbol{r}$. The received signal in vector notation is: $\boldsymbol{r} = \boldsymbol{s}_i + \boldsymbol{n}$, where $i = 1$ or 2. This geometric or vector view of signals and noise facilitates the discussion of digital signal detection. The vectors $\boldsymbol{s}_1$ and $\boldsymbol{s}_2$ are fixed, since the waveforms $s_1(t)$ and $s_2(t)$ are nonrandom. The vector or point $\boldsymbol{n}$ is a random vector; hence, $\boldsymbol{r}$ is also a random vector.

The detector's task after receiving $\boldsymbol{r}$ is to decide whether signal $\boldsymbol{s}_1$ or $\boldsymbol{s}_2$ was actually transmitted. The method is usually to decide upon the signal classification that yields the minimum P_E, although other strategies are possible [20]. For the case where M equals two signal classes, with $\boldsymbol{s}_1$ and $\boldsymbol{s}_2$ being equally likely and the noise being AWGN, the minimum-error decision rule turns out to be: Whenever the received signal $\boldsymbol{r}$ lands in region 1, choose signal $\boldsymbol{s}_1$; when it lands in region 2, choose signal $\boldsymbol{s}_2$ (see Fig. 4). An equivalent statement is: Choose the signal class such that the distance $d(\boldsymbol{r},\boldsymbol{s}_i) = \| \boldsymbol{r} - \boldsymbol{s}_i \|$ is minimal, where $\| \boldsymbol{x} \|$ is called the "norm" of vector $\boldsymbol{x}$ and generalizes the concept of length.

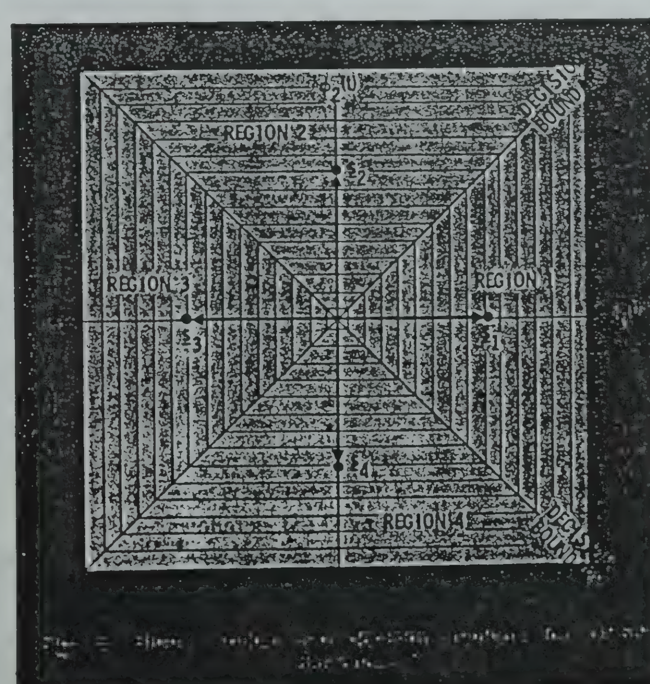
Detection of Coherent PSK

The receiver structure implied by the above rule is illustrated in Fig. 5. There is one product integrator (correlator) for each prototype waveform (M in all); the correlators are followed by a decision stage. The received signal is correlated with each prototype waveform known *a priori* to the receiver. The decision stage chooses the signal belonging to the correlator with the largest output (largest z_i). For example, let:

$s_1(t) = \sin \omega t$
$s_2(t) = -\sin \omega t$
$n(t) =$ a random process with zero mean and Gaussian distribution

Assume $s_1(t)$ was transmitted, so that:

$$r(t) = s_1(t) + n(t) \text{ and } z_i = \int_0^T r(t)\, s_i(t)\, dt \qquad i = 1,2$$



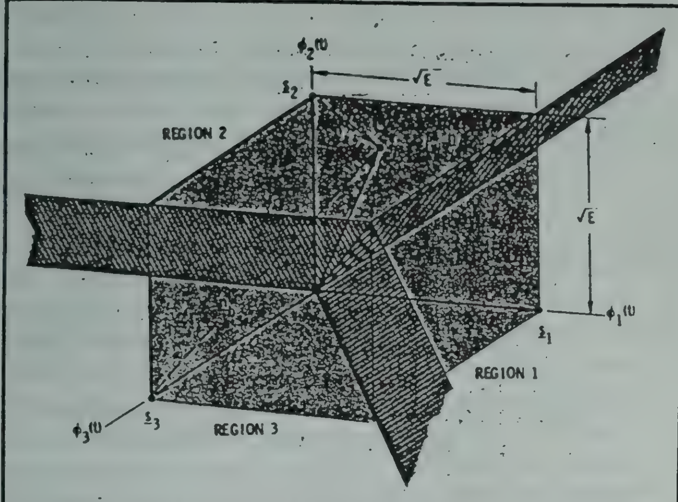


Fig. 7. Signal space and decision regions for 3-ary coherent FSK detection.

The expected values of the product integrators, as illustrated in Fig. 5, are found as follows:

$$E\left\{z_1(t=T)\right\} = E\left\{\int_0^T \sin^2 \omega t + n(t)\sin \omega t \, dt\right\} = T/2$$

$$E\left\{z_2(t=T)\right\} = E\left\{\int_0^T -\sin^2 \omega t + n(t)\sin \omega t \, dt\right\} = -T/2$$

where E is the statistical average.

The decision stage must decide which signal was transmitted by measuring its location within the signal space. The decision rule is to choose the signal with the largest value of z_i. Unless the noise is large and of a nature liable to cause an error, the received signal is judged to be $s_1(t)$. Note that in the presence of noise this process is statistical; the optimal detector is one that makes the fewest errors on the average. The only strategy that the detector can employ is to "guess" using some optimized decision rule.

Figure 6 shows the detection process with the signal space in mind. It represents a coherent four-level (4-ary) PSK or quadraphase shift keying (QPSK) system. In the terms we used earlier for M-ary signaling, $k = 2$ and $M = 2^2 = 4$. Binary source digits are collected two at a time, and for each symbol interval the two sequential digits instruct the modulator as to which of the four waveforms to produce. In general, for coherent M-ary PSK (MPSK) systems, $s_i(t)$ can be expressed as

$$s_i(t) = \sqrt{2E/T}\cos(\omega_0 t - 2\pi i/M) \qquad (\text{for } 0 \leq t \leq T) \quad i = 1, 2, \ldots, M$$

Here, E is the energy content of $s_i(t)$, and ω_0 is an integral multiple of $2\pi/T$. We can choose a convenient set of orthogonal axes scaled to fulfill (3) as follows

$$\phi_1(t) = \sqrt{2/T}\cos \omega_0 t \qquad (6)$$
$$\phi_2(t) = \sqrt{2/T}\sin \omega_0 t$$

Now $s_i(t)$ can be written in terms of these orthogonal coordinates, giving:

$$s_i(t) = \sqrt{E}\cos(2\pi i/M)\,\phi_1(t) + \sqrt{E}\sin(2\pi i/M)\,\phi_2(t) \quad (7)$$

The decision rule for the detector (see Fig. 6) is to decide that $s_1(t)$ was transmitted if the received signal point falls in region 1, that $s_2(t)$ was transmitted if the received signal point falls in region 2, and so forth. In other words, the decision rule is to choose the ith waveform with the largest value of correlator output z_i (see Fig. 5).

Detection of Coherent FSK

FSK modulation is characterized by the information being contained in the frequency of the carrier wave. A typical set of signal waveforms is described by

$$s_i(t) = \sqrt{2E/T}\cos \omega_i t \qquad (\text{for } 0 \leq t \leq T) \qquad i = 1, 2, \ldots, M$$
$$= 0 \qquad (\text{otherwise})$$

where E is the energy content of $s_i(t)$, and $(\omega_{i+1} - \omega_i)$ is an integral multiple of $2\pi/T$. The most useful form for the orthonormal coordinates $\phi_1(t), \phi_2(t), \ldots, \phi_N(t)$ is

$$\phi_j(t) = \sqrt{2/T}\cos \omega_j t \qquad j = 1, 2, \ldots, N$$

and, from (2)

$$a_{ij} = \int_0^T \sqrt{2E/T}\cos \omega_i t \sqrt{2/T}\cos \omega_j t \, dt.$$

Therefore

$$a_{ij} = \sqrt{E} \qquad (\text{for } i = j)$$
$$= 0 \qquad (\text{otherwise})$$

In other words, the ith signal point is located on the ith coordinate axis at a displacement $\sqrt{E}$ from the origin of the signal space. Figure 7 illustrates the signal vectors (points) and the decision regions for a 3-ary coherent FSK modulation ($M = 3$). In this scheme, the distance between any two signal points $\mathbf{s}_i$ and $\mathbf{s}_j$ is constant

$$d(\mathbf{s}_i, \mathbf{s}_j) = \| \mathbf{s}_i - \mathbf{s}_j \| = \sqrt{2E} \qquad (\text{for } i \neq j)$$

As in the coherent PSK case, the signal space is partitioned into M distinct regions, each containing one prototype signal point. The optimum decision rule is to decide that the transmitted signal belongs to the class whose index number is the same as the region where the received signal was found. In Fig. 7, a received signal point $\mathbf{r}$ is shown in region 2. Using the decision rule, the detector classifies it as signal $\mathbf{s}_2$. Since the

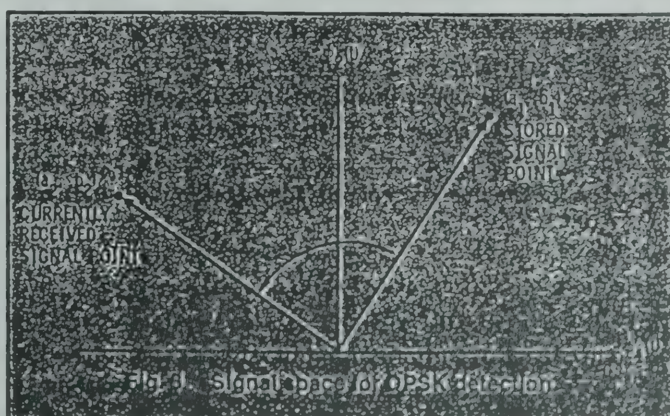


Fig. 8. Signal space for QPSK detection.

noise is a random vector, there is a probability greater than zero that the location of $\boldsymbol{r}$ is due to some signal other than $\boldsymbol{s}_2$. For example, if the transmitter sent $\boldsymbol{s}_2$, then $\boldsymbol{r}$ is the sum of $\boldsymbol{s}_2 + \boldsymbol{n}_a$, and the decision to choose $\boldsymbol{s}_2$ is correct; however, if the transmitter actually sent $\boldsymbol{s}_3$, then $\boldsymbol{r}$ must be the sum of $\boldsymbol{s}_3 + \boldsymbol{n}_b$ (see Fig. 7), and the decision to select $\boldsymbol{s}_2$ is an error.

Detection of DPSK

With noncoherent systems, no provision is made to phase-synchronize the receiver with the transmitter. Therefore, if the transmitted waveform is

$$s_i(t) = \sqrt{2E/T}\cos(\omega_0 t + \phi_i) \qquad i = 1, 2, \ldots, M$$

the received signal can be characterized by

$$r(t) = \sqrt{2E/T}\cos(\omega_0 t + \phi_i + \alpha) + n(t)$$

where α is unknown and is assumed to be randomly distributed between zero and 2π.

For coherent detection, product integrators (or their equivalents) are used; for noncoherent detection, this practice is generally inadequate because the output of a product integrator is a function of the unknown angle α. However, if we assume that α varies slowly enough to be considered constant over two period times ($2T$), the relative phase difference between two successive waveforms is independent of α, that is,

$$(\phi_1 + \alpha) - (\phi_2 + \alpha) = \phi_1 - \phi_2.$$

This is the basis for DPSK modulation. The carrier phase of the previous signaling interval is used as a phase reference for demodulation. Its use requires differential encoding of the message sequence at the transmitter since the information is carried by the difference in phase between two successive waveforms. To send the ith message ($i = 1, 2, \ldots, M$), the current signal waveform must have its phase advanced by $2\pi i/M$ radians over the previous waveform. The detector can then calculate the coordinates of the incoming signal by product-integrating it with the locally generated waveforms $\sqrt{2/T}\cos\omega_0 t$ and $\sqrt{2/T}\sin\omega_0 t$. In this way it measures the angle between the current and the previously received signal points (see Fig. 8) [19].

One way of viewing the difference between coherent PSK and DPSK is that the former compares the received signal with a clean reference; in the latter however, two noisy signals are compared with each other. Thus, we might say there is twice as much noise in DPSK as in PSK. Consequently, DPSK manifests a degradation of approximately 3 dB when compared with PSK; this number decreases rapidly with increasing signal-to-noise ratio. In general, the errors tend to propagate (to adjacent period times) due to the correlation between signaling waveforms. The trade-off for this performance loss is reduced system complexity.

Detection of Noncoherent FSK

A noncoherent FSK detector can be implemented with correlators such as those shown in Fig. 5. However, the hardware must be configured as an energy detector, without exploiting phase measurements. For this reason, it is implemented with twice as many channel branches as the coherent detector. Figure 9 illustrates the in-phase (I) channels and quadrature (Q) channels used to detect the signal set noncoherently. Another possible implementation uses filters followed by envelope detectors; the detectors are matched to the signal envelopes and not to the signals themselves. The phase of the carrier is of no importance in defining the envelope; hence, no phase information is used. In the case of binary FSK, the decision as to whether a "1" or a "0" was transmitted is made on the basis of which of the two envelope detectors has the largest amplitude at the moment of measurement. Similarly, for a multifrequency shift keying (M-ary FSK, or MFSK) system, the decision as to which of the M signals was transmitted is made on the basis of which of the M envelope detectors has maximum output.

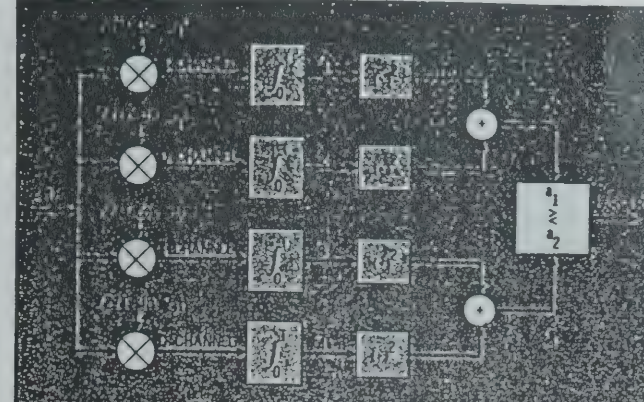


Fig. 9. Quadrature receiver.

Probability of Error

The calculations for probability of error (P_E), which can be viewed geometrically (see Fig. 4), involve finding the probability that given a particular signal, say $\boldsymbol{s}_1$, the noise vector $\boldsymbol{n}$ will give rise to a received signal falling outside region 1; all P_E calculations have this goal. For the general M-ary signaling case, the probability of making an incorrect decision is termed the probability of symbol error, or simply (P_E). It is often convenient to specify system performance by the probability of bit error (P_B), even when decisions are made on the basis of symbols for which $k > 1$. P_E and P_B are related as follows: For orthogonal signals [21],

$$P_B/P_E = (2^{k-1})/(2^k - 1).$$

For nonorthogonal schemes, such as MPSK signaling, one often uses a binary-to-M-ary code such that binary sequences corresponding to adjacent symbols (phase shifts) differ in only one bit position; one such code is the Gray code. When an M-ary symbol error occurs, it is more likely that only one of the k input bits will be in error. For such signals [3],

$$P_B \cong P_E/\log_2 M = P_E/k \qquad (\text{for } P_E << 1)$$

For convenience, this discussion is restricted to BPSK ($k = 1, M = 2$) modulation. For the binary case, the symbol error probability equals the bit error probability. Assume that signal $s_1(t)$ has been transmitted and that $r(t) = s_1(t) + n(t)$.

Assuming equally likely signals, and recalling that the decision of region 1 versus region 2 depends on the product integrators and the decision stage (see Fig. 5), we can write

$$P_E\Big]_{\text{binary}} = P_B = Pr\left[\int_0^T r(t)s_2(t)\,dt > \int_0^T r(t)s_1(t)\,dt \;\Big|\; r(t) = s_1(t) + n(t)\right]$$

for $0 \leqslant t \leqslant T$. The solution for the P_B expression can be shown to be

$$P_B = 1/\sqrt{2\pi}\int_{\sqrt{E_b/N_0(1-\cos\theta)}}^{\infty} \exp(-u^2/2)\,du$$

where E_b is the signal energy per bit in joules, N_0 is the noise density at the receiver in watts per Hz, and θ is the angle between $\mathbf{s}_1$ and $\mathbf{s}_2$ (see Fig. 4). When $\theta = \pi$, the signals are termed antipodal, and the P_B becomes

$$P_B = 1/\sqrt{2\pi}\int_{\sqrt{2E_b/N_0}}^{\infty} \exp(-u^2/2)\,du = Q(\sqrt{2E_b/N_0}) \quad (8)$$

The same kind of analysis is pursued in finding the P_B expressions for the other types of modulation. The parameter E_b/N_0 in (8) can be expressed as the ratio of average signal power to average noise power, S/N (or SNR). By arbitrarily introducing the baseband signal bandwidth W, we can write the following identities, showing the relationship between E_b/N_0 and SNR

$$E_b/N_0 = ST/N_0 = S/RN_0 = SW/RN_0W$$
$$= (S/N)(W/R) \quad (9)$$

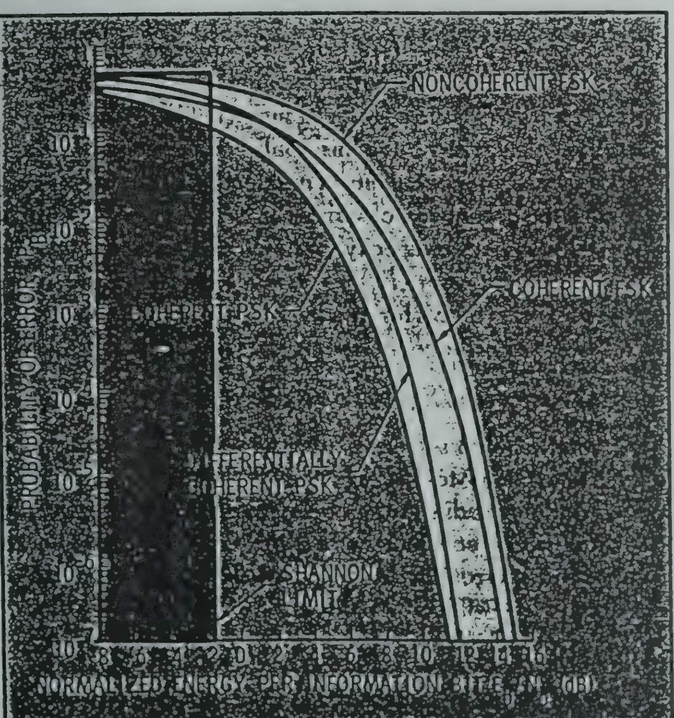


Fig. 10. Probability of bit error for selected binary modulation schemes.

TABLE I
Probability of Bit Error for Selected Binary Modulation Schemes

Modulation	P_B
Coherent PSK	$Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$
Noncoherent DPSK	$1/2 \exp(-E_b/N_0)$
Coherent FSK	$Q\left(\sqrt{\frac{E_b}{N_0}}\right)$
Noncoherent FSK	$1/2 \exp[-1/2(E_b/N_0)]$

where $\frac{E_b}{N_0} = \frac{\text{Energy/Bit}}{\text{Noise Density}}$

$= \frac{S}{N_0R} = \frac{\text{Signal Power}}{\text{Noise Density} \times \text{Bit Rate}}$

and $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} \exp(-u^2/2)du$

where S = average modulating signal power
T = bit time duration
$R = 1/T$ = bit rate
$N = N_0W$

The dimensionless ratio E_b/N_0 (required to achieve a specified P_B) is uniformly used for characterizing digital communications system performance. Note that optimum digital signal detection implies a correlator (or matched filter) implementation, in which case the signal bandwidth is equal to the noise bandwidth. Often we are faced with a system model for which this is not the case (less than optimum); in practice, we just reflect a factor into the required E_b/N_0 parameter that accounts for the suboptimal detection performance. Therefore, required E_b/N_0 can be considered a metric that characterizes the performance of one system versus another; the smaller the required E_b/N_0, the more efficient the system modulation and detection process.

The P_B expressions for the binary modulation schemes discussed above are listed in Table I and are graphically compared in Fig. 10. At large SNR's, it can be seen that there is approximately a 4-dB difference between the best (coherent PSK) and the worst (noncoherent FSK). In some cases, 4 dB is a small price to pay for the implementation simplicity gained in going from a coherent PSK to a noncoherent FSK; however, for some applications, even a 1-dB saving is worthwhile. There are other considerations besides P_B and system complexity; for example, in some cases (such as randomly fading propagation conditions), a noncoherent system is more robust and desirable because there may be difficulty in establishing a coherent reference.

An exception to Table I and Fig. 10 is worth mentioning, in light of today's bandwidth efficient modulation schemes. MSK modulation, which can be regarded as coherent FSK, manifests error-rate performance equal to BPSK when detected with the appropriate receiver [18].

Digital Transmission Trade-Offs

System trade-offs are fundamental to all digital communications designs. The goals of the designer are: (1) to

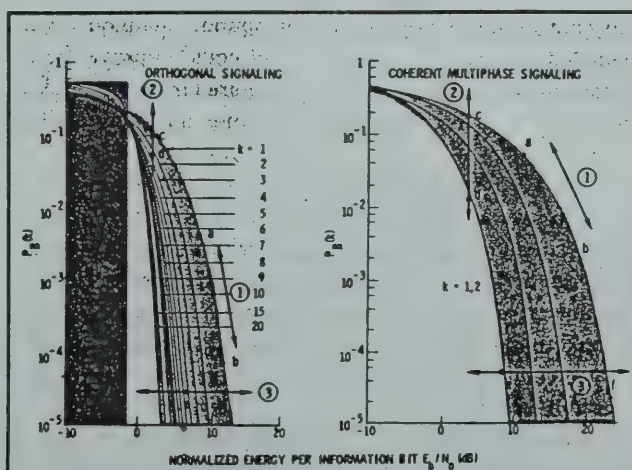
maximize transmission bit rate R, (2) to minimize probability of bit error P_B, (3) to minimize required power, or relatedly, to minimize required bit energy per noise density E_b/N_0, (4) to minimize required system bandwidth W, (5) to maximize system utilization, that is, to provide reliable service for a maximum number of users, with minimum delay and maximum resistance to interference, and (6) to minimize system complexity, computational load, and system cost. The designer usually seeks to achieve all these goals. However, goals (1) and (2) are clearly in conflict with goals (3) and (4); they call for simultaneously maximizing R, while minimizing P_B, E_b/N_0, and W. There are several constraints and theoretical limitations that necessitate the trading-off of any one requirement with each of the others. Some of the constraints are: the Nyquist theoretical minimum bandwidth requirement, the Shannon-Hartley capacity theorem, the Shannon limit, government regulations (for example, frequency allocations), technological limitations (for example, state-of-the-art components), and other system requirements (for example, satellite orbits).

M-ary Signaling and the Error-Rate Plane

Figure 11(a) illustrates the family of waterfall-like curves characterizing P_B versus E_b/N_0 for orthogonal signaling. Figure 11(b) illustrates similar curves for multiphase signaling [3]. As described in the earlier section on "Digital Modulation Formats", the signaling is called M-ary for modulation or coding schemes that process k bits at a time. The system directs the modulator to choose one of its $M = 2^k$ waveforms for each k bit sequence, where M is the symbol-set size, and k is the number of binary digits that each symbol represents. Figure 11(a) illustrates potential P_B improvement as k (or M) increases. For orthogonal signal sets, such as FSK modulation, M-ary signaling, compared to binary, can provide an improved P_B performance or a reduced E_b/N_0 requirement, at the cost of an increased bandwidth requirement. Figure 11(b) illustrates potential P_B degradation as k (or M) increases. For nonorthogonal signal sets, such as multiphase shift keying (MPSK) modulation, M-ary signaling, compared to binary, can provide a reduced bandwidth requirement, at the cost of a degraded P_B performance or an increased E_b/N_0 requirement. The appropriate Fig. 11 curve, from the family of curves depicting system performance, is a function of the system designer's choice of the parameter $k = \log_2 M$. We shall refer to either of these curve families (Fig. 11(a) or Fig. 11(b)) as error-rate performance curves, and to the plane upon which they are plotted as an error-rate plane. Such a plane describes the locus of operating points available for a particular type of modulation and coding. For a given system, each curve in the plane can be associated with a different fixed bandwidth; therefore, the set of curves can be termed equi-bandwidth curves. As the curves move in the direction of the ordinate, the required bandwidth grows, until it goes to infinity in the limit. As the curves move in the opposite direction, the required bandwidth decreases. Once a modulation, coding scheme, and available E_b/N_0 are chosen, system operation is characterized by a particular point in the error-rate plane. Possible trade-offs can be viewed as changes in the operating point on one of the curves, or as changes in the operating point from one curve to another curve of the family. Such potential trade-offs are seen in Figs. 11(a) and 11(b) as changes in operating point in the direction shown by the arrows. Movement of the operating point along line 1, between points a and b, can be viewed as trading P_B versus E_b/N_0 performance (with W fixed). Similarly, movement along line 2, between points c and d, is seen as trading P_B versus W performance (with E_b/N_0 fixed). Finally, movement along line 3, between points e and f, illustrates trading W versus E_b/N_0 performance (with P_B fixed). Movement along line 1 is effected simply by increasing or decreasing the available E_b/N_0. Movement along line 2 or line 3 is effected through an appropriate change to the system modulation or coding scheme.

The Nyquist and Shannon Constraints

Symbol detection in a realizable system, even in the absence of noise, suffers from intersymbol interference, ISI; the tail of one pulse spills over into adjacent symbol intervals so as to interfere with correct detection. Nyquist [22,23] showed that the theoretical minimum bandwidth needed to transmit x symbols per second (symbols/s) without ISI is $x/2$ Hz; this is a basic theoretical constraint, limiting the designer's goal to expend as little bandwidth as possible. In practice, it typically requires x Hz bandwidth for the transmission of x symbols/s. In other words, typical digital communication throughput without ISI is limited to 1 symbol/s/Hz. For a fixed bandwidth, as k (and M) increases, the bandwidth efficiency R/W, measured in b/s/Hz, increases. For example, movement along line 3, from point e to point f, in Fig. 11(b) represents trading E_b/N_0 for a reduced bandwidth requirement; in other words, with the same system bandwidth one can transmit at an increased data rate, hence at an increased R/W.



(a) (b)

Fig. 11. The error-rate plane.

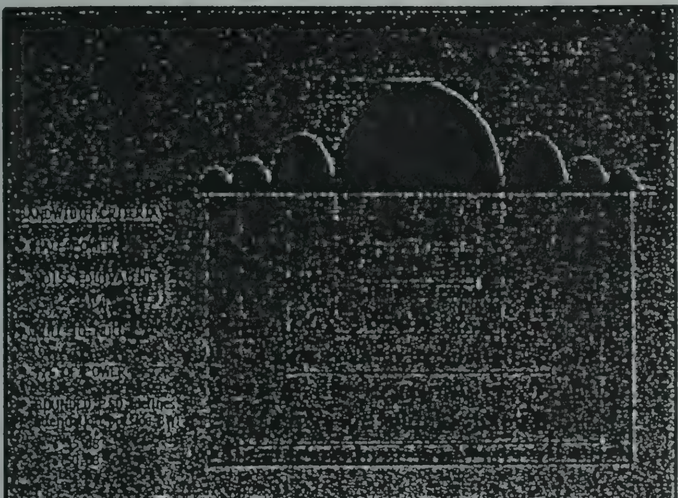


Fig. 12. Various bandwidth criteria.

Shannon [24] showed that the system capacity C, for channels perturbed by AWGN, is a function of the average received signal power S; the average noise power N; and the bandwidth W. The capacity relationship (Shannon-Hartley theorem) can be stated as:

$$\begin{aligned} C &= W \log_2 (1 + S/N) \\ &= W \log_2 \left[1 + E_b/N_0\,(C/W)\right] \end{aligned} \tag{10}$$

It is possible to transmit information over such a channel at a rate R, where $R \leqslant C$, with an arbitrarily small error rate by using a sufficiently complicated coding scheme. For a rate $R > C$, it is not possible to find a code which can achieve an arbitrarily small error rate. Shannon's work showed that the values of S, N, and W set a limit on transmission rate, not on accuracy. It can also be shown, from (10), that the required E_b/N_0 approaches the Shannon limit of -1.6 dB as W increases without bound. At the Shannon limit, shown in Fig. 11(a), and P_B curve is discontinuous, going from a value of $P_B = 1/2$ to $P_B = 0$. It is not possible to reach the Shannon limit, because, as k increases without bound, the bandwidth requirement and delay become infinite and the implementation complexity increases without bound. Shannon's work predicted the existence of codes that could improve the P_B performance or reduce the E_b/N_0 required from the levels of the uncoded binary modulation schemes up to the limiting curve. For $P_B = 10^{-5}$, BPSK modulation requires an E_b/N_0 of 9.6 dB (the optimum uncoded binary case). Shannon's work therefore promised a theoretical performance improvement of 11.2 dB over the performance of optimum uncoded binary modulation, through the use of coding techniques. Today, most of that promised improvement (approximately 7 dB) is realizable [25]. Optimum system design can best be described as a search for rational compromises or trade-offs amongst the various constraints and conflicting goals.

Bandwidth of Digital Data

The theorems of Nyquist and Shannon, though concise and fundamental, are based on the assumption of strictly band-limited channels, which means that no signal power whatever is allowed outside the defined band. We are faced with the dilemma that strictly band-limited signals are not realizable since they imply infinite transmission-time delay; non-band-limited signals, having energy at arbitrarily high frequencies, appear just as unreasonable [26]. It is no wonder that there is no single universal definition of bandwidth.

All criteria of bandwidth have in common the attempt to specify a measure of the width W of a non-negative real-valued spectral density defined for all frequencies $|f| < \infty$. Figure 12 illustrates some of the most common definitions of bandwidth; in general, the various criteria are not interchangable [27]. The power spectral density $S(f)$ for a single pulse takes the analytical form

$$S(f) = T\left[\frac{\sin \pi(f - f_c)T}{\pi(f - f_c)T}\right]^2$$

where f_c is the carrier frequency and T is the symbol duration. This same spectral density, whose general appearance is sketched in Fig. 12, characterizes a sequence of random digital data, assuming the averaging time is long, relative to the symbol duration [28]. The spectral density plot consists of a main lobe and smaller symmetrical side lobes. The general shape of the plot is valid for most digital modulation formats; some formats, however, do not have well defined lobes [28]. The bandwidth criteria depicted in Fig. 12 are:

1) Half-Power Bandwidth: This is the interval between frequencies at which $S(f)$ has dropped to half power, or 3 dB below the peak value.
2) Equivalent Rectangular or Noise Equivalent Bandwidth: The noise equivalent bandwidth was originally conceived to permit rapid computation of output noise-power from an amplifier with a wide-band noise input; the concept can similarly be applied to a signal bandwidth. The noise equivalent bandwidth of a signal is defined as the value of bandwidth which satisfies the relationship $P = W_N\, S(f_c)$, where P is the total signal power over all frequencies, W_N is the noise equivalent bandwidth, and $S(f_c)$ is the value of $S(f)$ at the band center (assumed to be the maximum value over all frequencies).
3) Null-to-Null Bandwidth: The most popular measure of bandwidth is the width of the main spectral lobe, where most of the signal power is contained. This criterion lacks complete generality since some modulation formats lack well-defined lobes.
4) Fractional Power Containment Bandwidth: This bandwidth criterion has been adopted by the Federal Communications Commission (FCC Rules and Regulations Section 2.202) and states that the occupied bandwidth is the band which leaves exactly 0.5% of the signal power above the upper band limit and exactly 0.5% of the signal power below the lower band limit. Thus, 99% of the signal power is inside the occupied band.

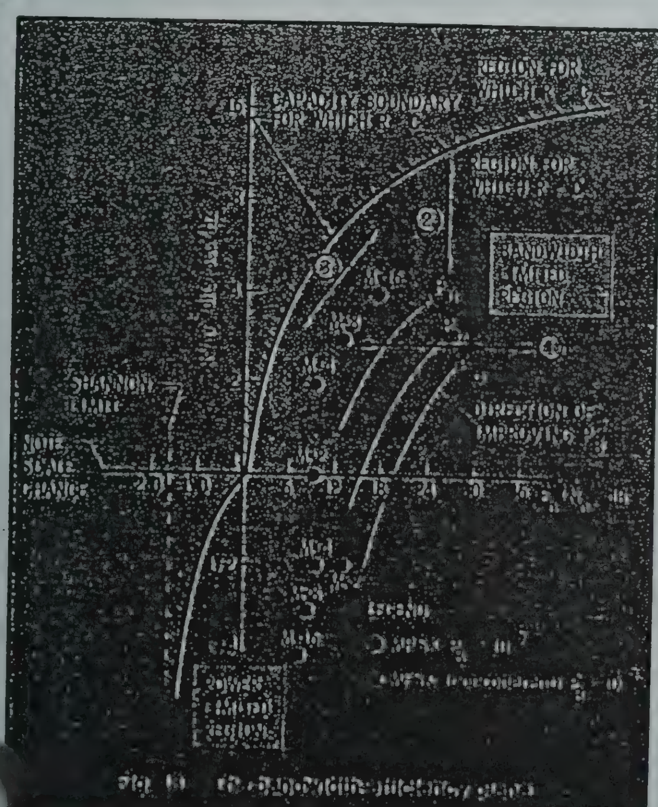
5) Bounded Power Spectral Density: A popular method of specifying bandwidth is to state that everywhere outside the specified band *S(f)* must have fallen at least to a certain stated level below that found at the band center. Typical attenuation levels might be 35 or 50 dB.

The Bandwidth-Efficiency Plane

Equation (10) can be written as

$$E_b/N_0 = W/C\,(2^{C/W} - 1). \tag{11}$$

Equation (11) has been plotted on the R/W versus E_b/N_0 plane in Fig. 13. We shall term this plane the bandwidth-efficiency plane. The ordinate R/W is a measure of how much data can be transmitted in a specified bandwidth within a given time; it therefore reflects how efficiently the bandwidth resource is utilized. The abscissa is E_b/N_0 in decibels. For $C = R$ in (11), the plotted curve in the plane represents a boundary that separates parameter combinations supporting potential error-free communication from regions where such communication is not possible. Upon the bandwidth-efficiency plane of Fig. 13 are plotted the operating points for MPSK and MFSK modulation, each at $P_B = 10^{-5}$. Notice that for MPSK modulation, R/W increases with increasing M; however, for MFSK modulation, R/W decreases with increasing M. Notice also that the location of the MPSK points indicate that BPSK ($M = 2$) and QPSK ($M = 4$) require the same E_b/N_0. That is, for the same value of E_b/N_0, QPSK has a bandwidth efficiency of 2 b/s/Hz, compared to 1 b/s/Hz for BPSK. This unique feature stems from the fact that QPSK is effectively a composite of two BPSK signals, transmitted on waveforms orthogonal to one another and having the same spectral occupancy. This same feature is illustrated in Fig. 11(b), where it can be seen that QPSK ($k = 2$) signaling has the same P_B (not the same symbol error rate) as does BPSK ($k = 1$) signaling. Each of the two orthogonal BPSK signals comprising QPSK yields half the bit rate and half the signal power of the QPSK signal; hence the required E_b/N_0 for a given P_B is identical for BPSK and QPSK. Also plotted on the bandwidth-efficiency plane of Fig. 13 are the operating points for noncoherent MFSK modulation at a BER of 10^{-5}. Notice that the position of the MFSK points indicates that binary FSK, BFSK ($M = 2$) and quarternary FSK (QFSK ($M = 4$)) have the same bandwidth efficiency, even though the former requires greater E_b/N_0 for the same error rate. The bandwidth efficiency varies with the modulation index; if we assume that an equal increment of bandwidth is required for each MFSK tone the system must support, it can be seen that for $M = 2$, $R/W = 1$ b/s/2 Hz $= 1/2$; and for $M = 4$, similarly, $R/W = 2$ b/s/4 Hz $= 1/2$.



The bandwidth-efficiency plane in Fig. 13 is analogous to the error-rate plane shown in Fig. 11. The Shannon limit of the Fig. 11 plane is analogous to the capacity boundary of the Fig. 13 plane. The curves in Fig. 11 were referred to as equi-bandwidth curves. In Fig. 13, we can analogously describe equi-error-probability curves for various modulation and coding schemes. The curves labeled P_{B1}, P_{B2}, and P_{B3} are hypothetical constructions for some arbitrary modulation and coding scheme; the P_{B1} curve represents the largest error probability of the three curves, and the P_{B3} curve represents the smallest. The general direction in which the curves move for improved P_B is indicated on the figure.

Just as potential trade-offs amongst P_B, E_b/N_0, and W were considered for the error-rate plane, so too we can view the same trade-offs on the bandwidth-efficiency plane. Such potential trade-offs are seen in Fig. 13 as changes in operating point in the direction shown by the arrows. Movement of the operating point along line 1 can be viewed as trading P_B versus E_b/N_0 performance, with R/W fixed. Similarly, movement along line 2 is seen as trading P_B versus W (or R/W) performance, with E_b/N_0 fixed. Finally, movement along line 3 illustrates trading W (or R/W) versus E_b/N_0 performance, with P_B fixed. In Fig. 13, as in Fig. 11, movement along line 1 is effected simply by increasing or decreasing the available E_b/N_0. Movement along line 2 or line 3 is effected through appropriate changes to the system modulation or coding scheme.

Power-Limited Systems and Bandwidth-Limited Systems

For the case of power-limited systems, in which power is scarce but system bandwidth is available (for example, a space communication link), the following tradeoffs might be made:

- Improved P_B performance can be achieved by expending bandwidth (for a given E_b/N_0).

- Required E_b/N_0 can be reduced by expending bandwidth (for a given P_B).

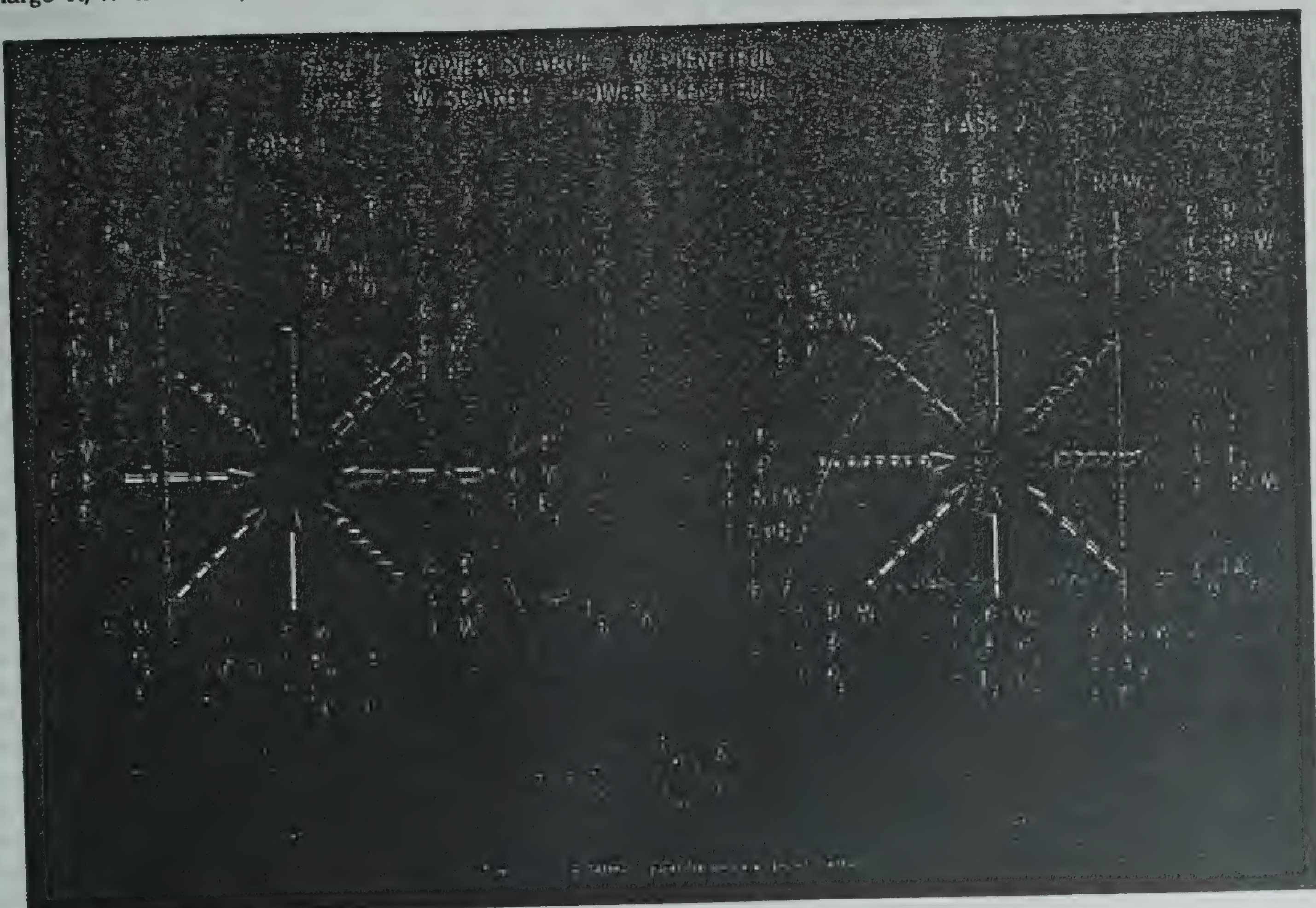
The error-rate plane of Fig. 11(a) is most useful for examining such potential trade-offs. It is on this plane that we can verify whether or not a candidate code offers improvement in required E_b/N_0 (coding gain) for a specified P_B (or whether the code offers improvement in P_B for a given E_b/N_0).

Any digital scheme that transmits $R = \log_2 M$ bits in T seconds, using a bandwidth of W Hz, always operates at a bandwidth efficiency of $R/W = (\log_2 M)/WT$ b/s/Hz. From this expression, it can be seen that signals with small WT products are most bandwidth-efficient. Such signals are generally associated with bandwidth-limited systems in which channel bandwidth is constrained but power is abundant. For this case, the usual objective is to design the link so as to maximize the transmitted data rate over the band-limited channel, at the expense of E_b/N_0 (while maintaining a specified P_B performance level). For band-limited operation, bandwidth efficiency is a useful criterion of system performance, and the bandwidth-efficiency plane of Fig. 13 is useful for examining potential trade-offs, such as E_b/N_0 for improved R/W, or degraded P_B for improved R/W.

The bandwidth-limited and power-limited regions are shown on the bandwidth-efficiency plane of Fig. 13. Notice that the desirable trade-offs associated with each of these regions are not equitable. For the bandwidth-limited region, large R/W is desired; however as E_b/N_0 is continually increased, the capacity boundary curve flattens out, and ever-increasing amounts of E_b/N_0 are required to achieve improvement in R/W. A similar law of nature seems to be at work in the power-limited region. Here, a savings in E_b/N_0 is desired, but the capacity boundary curve is steep; to achieve a small relief in required E_b/N_0 requires a large reduction in R/W (increase in bandwidth for a given data rate).

Digital Communication Tradeoffs

Figure 14 has been configured for pointing out analogies between the two performance planes, the error-rate plane of Fig. 11, and the bandwidth-efficiency plane of Fig. 13. Figures 14(a) and 14(b) represent the same planes as Figs. 11 and 13, respectively. They have been redrawn, purposely symmetrical, by choosing appropriate scales. The arrows and their labels, in each case, describe the general effect of moving an operating point in the direction of the arrow by means of appropriate modulation and coding techniques. The notations G, C, and F stand for the trade-off considerations "Gained or achieved," "Cost or expended," and "Fixed or unchanged," respectively. The parameters being traded are P_B, W, R/W, and P (power or S/N). Just as the movement of an operating point toward the Shannon limit in Fig. 14(a) gains improved P_B or lower transmitter power at the cost of bandwidth, so too does movement toward the capacity boundary in Fig. 14(b) gain improved bandwidth efficiency at the cost of increased power or degraded P_B.



Most often, such trade-offs are examined with a fixed P_B (constrained by the system requirement) in mind. Therefore, the most interesting arrows are those having fixed bit-error probability (marked $F: P_B$). There are four such arrows in Fig. 14, two on the error-rate plane and two on the bandwidth-efficiency plane. System operation can be characterized by either of these two planes. The planes represent two ways of looking at some of the key system parameters; each plane highlights slightly different aspects of the overall design problem. The error-rate plane tends to find most use with power-limited systems; here, as we move from curve to curve, the bandwidth requirements are only inferred, but the P_B is clearly displayed. The bandwidth-efficiency plane is generally more useful for examining bandwidth-limited systems; here, as we move from curve to curve, P_B is only inferred, but the bandwidth requirements are explicit, since the ordinate is R/W.

Additional Constraints

We are not as free to make trade-offs as we might like. Government regulations dictate choice of frequencies, bandwidths, transmission power levels, and in the case of satellites, orbit selection. The satellite orbit and geometry of coverage fixes the satellite antenna gain. Technological state-of-the-art constrains such items as satellite power transmission and earth station antenna gain. There may be other system requirements (for example, the need to operate under scintillation or interference conditions) that can influence the choice of modulation and coding. The effect of these additional constraints is to limit the regions of realizable operation within the error-rate plane and the bandwidth-efficiency plane.

Conclusion

In the first part of this paper, we have generated a structure and hierarchy of key signal processing transformations. We have used this structure as a guide for overviewing the formatting, source coding, and modulation steps. We have also examined potential trade-offs for power-limited systems and bandwidth-limited systems. In Part II we will continue to examine the remainder of the signal processing steps outlined in Figs. 1 and 2. Also in Part II, we will review fundamental link analysis relationships in the context of a satellite repeater channel.

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Bernard Sklar was born in New York, NY on September 11, 1927. He received the B.S. degree in mathematics and science from the University of Michigan, Ann Arbor, MI, in 1949; the M.S.E.E. degree from the Polytechnic Institute of New York, Brooklyn, NY, in 1958; and the Ph.D. degree in engineering from the University of California, Los Angeles, CA, in 1971.

Dr. Sklar has 30 years of experience with the aerospace/defense industry in a variety of technical design and management positions: from 1953 to 1958 he was a research engineer with Republic Aviation Corp., Farmingdale, NY; from 1958 to 1959 he was a member of the technical staff at Hughes Aircraft Co., Culver City, CA; and from 1959 to 1968 he was a senior staff engineer at Litton Systems, Inc., Canoga Park, CA. In 1968 he joined The Aerospace Corp., El Segundo, CA, where he is currently employed. As Manager of System Analysis, he is involved in the development of satellite communication systems.

He has taught engineering courses during the past 25 years at the University of California, Los Angeles and Irvine: the University of Southern California, Los Angeles; and West Coast University, Los Angeles. Dr. Sklar is a past chairman of the Los Angeles Council IEEE Education Committee, and has been a Senior Member of the IEEE since 1958. ■

Commercial Satellite Communication Applications

Course No. 9SV109

Reference 2

Guide to Metric Practice

GUIDE FOR METRIC PRACTICE

Internationally recognized conventions have been established for standard usage of SI units.

Robert A. Nelson

ROBERT NELSON is the author of the booklet *SI: The International System of Units*, 2nd ed. (American Association of Physics Teachers, College Park, Maryland, 1982). He is president of Satellite Engineering Research Corporation, a consulting firm in Bethesda, Maryland, and teaches in the department of aerospace engineering at the University of Maryland.

The modernized metric system is known as the Système International d'Unités (International System of Units), with the international abbreviation SI. It is founded on seven base units, listed in table 1, that by convention are regarded as dimensionally independent. All other units are derived units, formed coherently by multiplying and dividing units within the system without numerical factors. Examples of derived units, including some with special names, are listed in table 2. The expression of multiples and submultiples of SI units is facilitated through the use of the prefixes listed in table 3.

SI obtains its international authority from the Meter Convention, signed in Paris by the delegates of 17 countries, including the United States, on 20 May 1875, and amended in 1921. Today 48 states are members. The treaty established the Conférence Générale des Poids et Mesures (General Conference on Weights and Measures) as the formal diplomatic body responsible for ratification of new proposals related to metric units. The scientific decisions are made by the Comité International des Poids et Mesures (International Committee for Weights and Measures). It is assisted by the advice of eight Consultative Committees specializing in particular areas of metrology. The activities of the national standards laboratories are coordinated by the Bureau International des Poids et Mesures (International Bureau of Weights and Measures), whose headquarters is at the Pavillon de Breteuil in Sèvres, France, and which is under the supervision of the CIPM. The SI was established by the 11th CGPM in 1960, when the metric unit definitions, symbols and terminology were extensively revised and simplified.[1]

The BIPM, with the guidance of the Consultative Committee for Units and approval of the CIPM, periodically publishes a document[2] that summarizes the historical decisions of the CGPM and the CIPM and gives some conventions for metric practice. In addition, Technical Committee 12 of the International Organization for Standardization has prepared recommendations concerning the practical use of the SI.[3] Some other recommendations have been given by the Commission for Symbols, Units, Nomenclature, Atomic Masses and Fundamental Constants of the International Union of Pure and Applied Physics.[4] The National Institute of Standards and Technology has published a practical guide for the use of the SI.[5] The Institute of Electrical and Electronics Engineers has developed a metric practice manual[6] that has been recognized by the American National Standards Institute and has been adopted by the US Department of Defense. The American Society for Testing and Materials has prepared a similar manual.[7] The Secretary of Commerce, through NIST, has also issued recommendations for US metric practice,[8] as provided under the Metric Conversion Act of 1975 and the Omnibus Trade and Competitiveness Act of 1988. References 2, 5 and 8 are available on the Internet at http://physics.nist.gov/SI.

TABLE 1. SI base units

Quantity	Unit	
	Name	Symbol
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

TABLE 2. Examples of SI derived units

Quantity	Unit		
	Special name	Symbol	Equivalent
plane angle	radian	rad	m/m = 1
solid angle	steradian	sr	$m^2/m^2 = 1$
speed, velocity			m/s
acceleration			m/s^2
angular velocity			rad/s
angular acceleration			rad/s^2
frequency	hertz	Hz	s^{-1}
force	newton	N	$kg \cdot m/s^2$
pressure, stress	pascal	Pa	N/m^2
work, energy, heat	joule	J	$N \cdot m$, $kg \cdot m^2/s^2$
impulse, momentum			$N \cdot s$, $kg \cdot m/s$
power	watt	W	J/s
electric charge	coulomb	C	$A \cdot s$
electric potential, emf	volt	V	J/C, W/A
resistance	ohm	Ω	V/A
conductance	siemens	S	A/V, Ω^{-1}
magnetic flux	weber	Wb	$V \cdot s$
inductance	henry	H	Wb/A
capacitance	farad	F	C/V
electric field strength			V/m, N/C
magnetic flux density	tesla	T	Wb/m^2, $N/(A \cdot m)$
electric displacement			C/m^2
magnetic field strength			A/m
Celsius temperature	degree Celsius	°C	K
luminous flux	lumen	lm	$cd \cdot sr$
illuminance	lux	lx	lm/m^2
radioactivity	becquerel	Bq	s^{-1}

Style conventions

Letter symbols include quantity symbols and unit symbols. Symbols for physical quantities are set in italic (sloping) type, while symbols for units are set in roman (upright) type (for example, F = 15 N).

A unit symbol is a universal mathematical entity. It is not an abbreviation and is not followed by a period (for example, the symbol for second is s, not sec or s.). Symbols for units with proper names have the first letter capitalized—otherwise unit symbols are lower case—but the unit names themselves are not capitalized (for example, tesla, T; meter, m). In contrast to unit symbols, the spelling

TABLE 3. SI prefixes

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	μ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka	da	10^{-24}	yocto	y

TABLE 4. Units accepted for use with the SI

Quantity	Unit		
	Name	Symbol	Definition
time	minute	min	1 min = 60 s
	hour	h	1 h = 60 min = 3600 s
	day	d	1 d = 24 h = 86 400 s
plane angle	degree	°	1° = (π/180) rad
	minute	′	1′ = (1/60)° = (π/10 800) rad
	second	″	1″ = (1/60)′ = (π/648 800) rad
volume	liter	L	1 L = 1 dm^3 = 10^{-3} m^3
mass	metric ton	t	1 t = 1000 kg
attenuation, level	neper	Np	1 Np = 1
	bel	B	1 B = ½ ln 10 Np

TABLE 5. Units accepted for use with the SI whose values in SI units are obtained experimentally

Quantity	Unit		
	Name	Symbol	Value
energy	electron volt	eV	1.602 177 33(49)×10^{-19} J
mass	unified atomic mass unit	u	1.660 540 2(10)×10^{-27} kg
distance	astronomical unit	ua	1.495 978 706 91 (30) × 10^{11} m

and grammar for unit names are specific to a given language and are not part of the SI. For example, the spellings kilogram and ampere are used in English, while kilogramme and ampère are used in French, but kg and A are the universal SI symbols. Plurals of unit names are formed according to the usual rules of grammar (for example, kilopascals, henries) with the exceptions lux, hertz and siemens, which are irregular.[5] Unit symbols are not pluralized (for example, 3 kg, not 3 kgs).

The word "degree" and its symbol, °, are omitted from the unit of thermodynamic temperature T (that is, one uses kelvin or K, not degree Kelvin or °K). However, they are retained in the unit of Celsius temperature t, defined as $t \equiv T - T_0$, where T_0 = 273.15 K exactly (that is, degree Celsius, °C).

Symbols for prefixes representing 10^6 or greater are capitalized; all others are lower case. There is no space between the prefix and the unit. Compound prefixes are to be avoided (for example, pF, not μμF). An exponent applies to the whole unit including its prefix (for example, $cm^3 = 10^{-6}$ m^3). When a unit multiple or submultiple is written out in full, the prefix should be written in full, beginning with a lower-case letter (for example, megahertz, not Megahertz or Mhertz). The kilogram is the only base unit whose name, for historical reasons, contains a prefix; names of multiples and submultiples of the kilogram and their symbols are formed by attaching prefixes to the word "gram" and the symbol "g."

Multiplication of units is indicated by inserting a raised dot or by leaving a space between the units (for example, N·m or N m). Division may be indicated by the use of the solidus, a horizontal fraction bar or a negative exponent (for example, m/s, $\frac{m}{s}$ or $m{\cdot}s^{-1}$), but repeated use of the solidus is not permitted (for example, m/s^2, not m/s/s). To avoid possible misinterpretation when more than one unit appears in the denominator, the preferred practice is to use parentheses or negative exponents (for example, $W/(m^2{\cdot}K^4)$ or $W{\cdot}m^{-2}{\cdot}K^{-4}$). The unit expression may include a prefixed unit (for example, kJ/mol, W/cm^2).

Unit names should not be mixed with symbols for mathematical operations. (For example, one should write "meter per second" but not "meter/second" or "meter second^{-1}.") When spelling out the product of two units, a space is recommended (although a hyphen is permissible), but one should never use a centered dot. (Write, for example, "newton meter" or "newton-meter," but not "newton·meter.")

Three-digit groups in numbers with more than four digits are separated by thin spaces instead of commas (for example, 299 792 458, not 299,792,458) to avoid confusion with the decimal marker in European literature. This spacing convention is also used to the right of the decimal marker. The numerical value and unit symbol must be separated by a space, even when used as an adjective (for example, 35 mm, not 35mm or 35-mm). A zero should be placed in front of the decimal marker in decimal fractions (for example, 0.3 J, not .3 J). The prefix of a unit should be chosen so that the numerical value will be within a practical range, usually between 0.1 and 1000 (for example, 200 kN, 0.5 mA).

Non-SI units

An important function of the SI is to discourage the proliferation of unnecessary units. However, there are three categories of units outside the SI that are recognized. "Units accepted for use with the SI" are listed in Table 4. As exceptions to the rules, the symbols °, ′ and ″ for plane angle are not preceded by a space, and the symbol for liter, L, is capitalized to avoid confusion with the number 1. "Units accepted for use with the SI whose values in SI units are obtained experimentally" are given in Table 5. The third category, "other units currently accepted for use with the SI," include the nautical mile, knot, are, hectare, bar, angstrom and barn.

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Commercial Satellite Communication Applications
Course No. 9SV109

Reference 2

Telecommunications for the 21st Century

Commercial Satellite Communication Applications

Course No. 9SV109

Reference 3

Telecommunications for the 21st Century

Telecommunications for the 21st Century

Systems based on satellites and high-altitude platforms will merge with optical-fiber and terrestrial wireless networks to provide global, high data-rate, mobile communications

by Joseph N. Pelton

Space-based telecommunications systems will change our lives over the next two decades, providing rapid access to information of all types, from handheld or briefcase-size terminals anywhere on the planet. Mass virtual-reality entertainment, videos on demand and expanded tele-health and tele-education services are just some of the developments we can expect to arrive with this torrent of data—along with mounting information overload and the 168-hour workweek.

In five years' time there will very likely be 1,000 commerical communications satellites in service, up from about 220 today. Many of these switching stations in the sky will zoom in low earth orbit (LEO) only a few hundred kilometers overhead. But satel-

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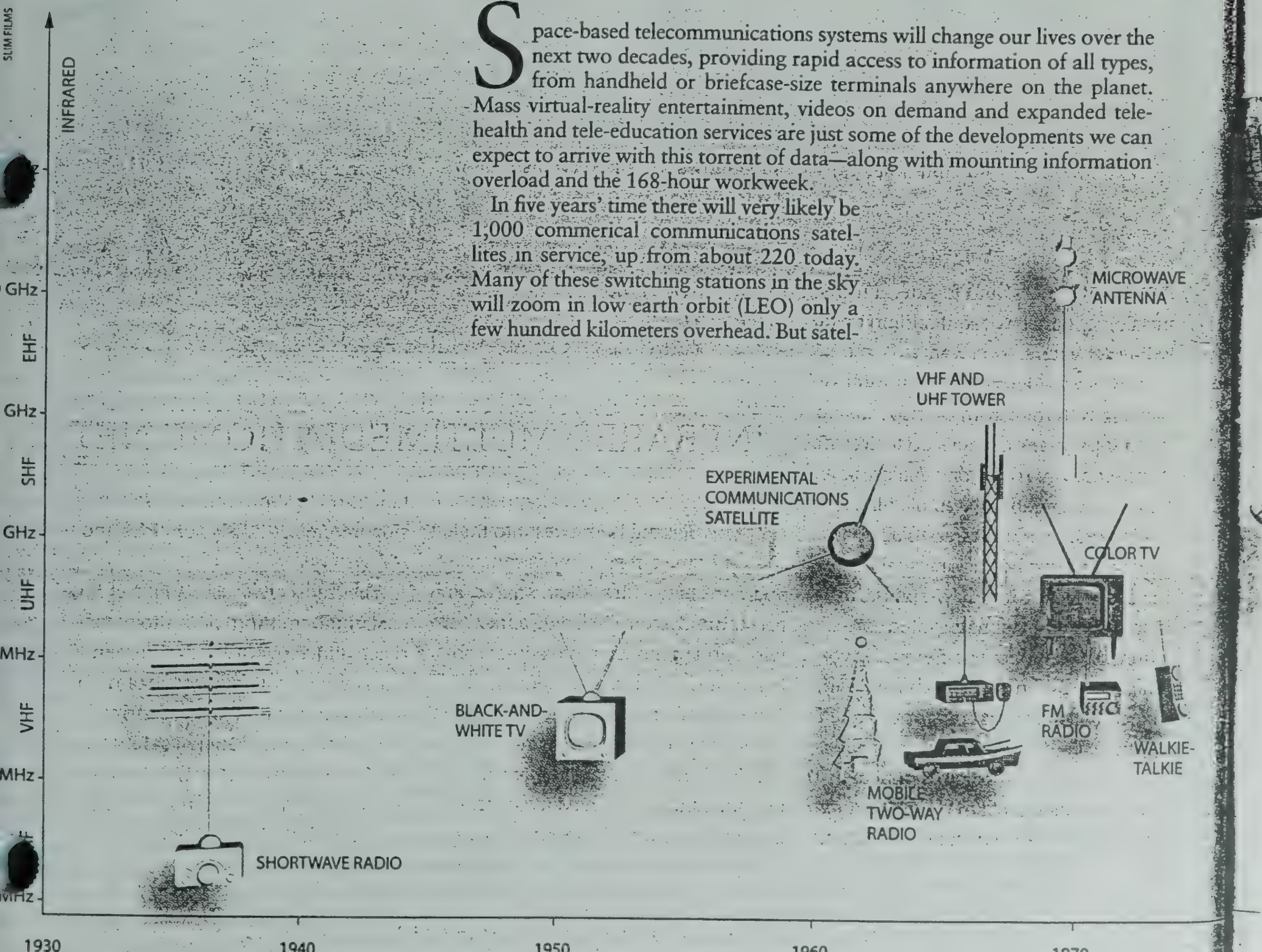


ites in the more traditional geosynchronous earth orbit (GEO), which turn with the earth 36,000 kilometers (22,300 miles) up, will remain very much in the picture.

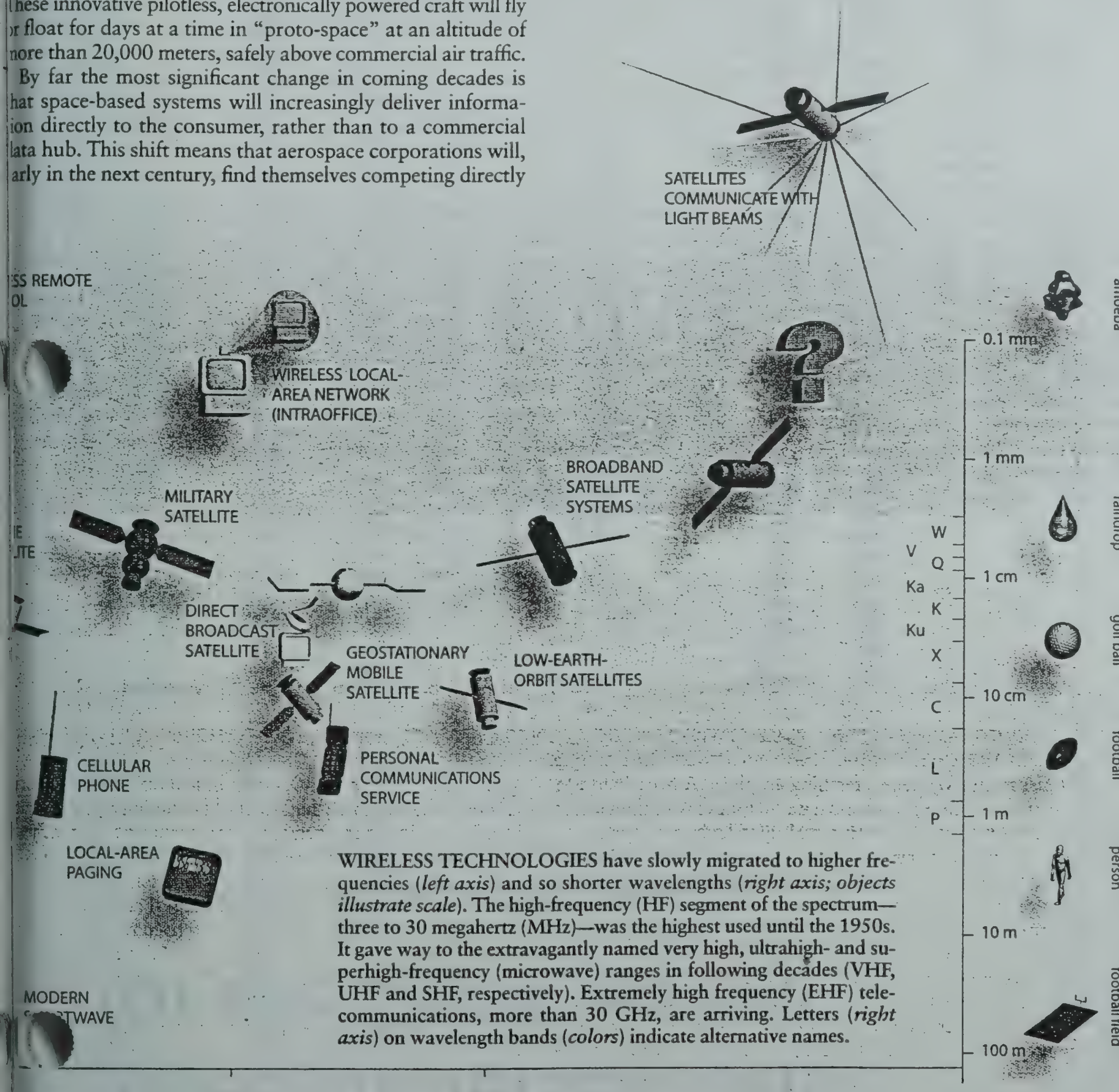
The proximity of LEO satellites offers some important advantages over today's orbiters. Signals will zip back and forth to orbits in hundredths of a second, a decisive advantage over the quarter of a second that data take to travel to and from GEO. On the pro side of the ledger, this faster performance will make interactive global access to networks and video teleconferencing practical and appealing. On the con side, LEO systems require 20 times more satellites than a GEO system to cover the globe and five times more than a medium-earth-orbit (MEO) network.

Satellites will soon not be the only type of space-based telecommunications system. By the year 2000 we could see High Altitude Long Endurance (HALE) platforms hovering over cities and beaming down thousands of data-rich signals. These innovative pilotless, electronically powered craft will fly or float for days at a time in "proto-space" at an altitude of more than 20,000 meters, safely above commercial air traffic.

By far the most significant change in coming decades is that space-based systems will increasingly deliver information directly to the consumer, rather than to a commercial data hub. This shift means that aerospace corporations will, early in the next century, find themselves competing directly with AT&T, MCI, British Telecom (BT) and other carriers.

Only a few years ago cumbersome dish antennas were needed to obtain a satellite connection faster than simple telephone service. Moreover, such links were in short supply, and service at sea cost as much as $10 per minute. Those limitations are disappearing. The coming torrent of high-speed data from space should be a colossal boon for individuals and corporations around the world. It will be especially important in developing countries such as Brazil, India and China, which do not have extensive fiber-optic networks.

The key innovation for handling the burgeoning demand is the phased-array antenna. This sophisticated electronic device, used until now mainly for military communications, consists of multiple transmitting elements arranged in a fixed geometric array. Arrays can be programmed to send a grid of electronically formed radio beams to track moving targets or,



WIRELESS TECHNOLOGIES have slowly migrated to higher frequencies (*left axis*) and so shorter wavelengths (*right axis; objects illustrate scale*). The high-frequency (HF) segment of the spectrum—three to 30 megahertz (MHz)—was the highest used until the 1950s. It gave way to the extravagantly named very high, ultrahigh- and superhigh-frequency (microwave) ranges in following decades (VHF, UHF and SHF, respectively). Extremely high frequency (EHF) telecommunications, more than 30 GHz, are arriving. Letters (*right axis*) on wavelength bands (*colors*) indicate alternative names.

alternatively, to receive signals from only certain directions.

In concept, these antennas are something like miniature versions of the Very Large Array, the cluster of radio telescopes in Socorro, N.M., used for studying astrophysical phenomena. Phased arrays achieve directional selectivity by electronically imposing minute delays on the signals moving from (or to) different parts of the array. Beams focused in this way reduce interference, an important advantage in view of the growing demand for radio spectrum. The pressure on spectrum will intensify, because high data-rate signals need much more bandwidth—a far bigger slice of spectrum—than do low data rates.

Mounted on satellites, phased arrays can steer beams as little as half a degree across toward their intended recipients. Moreover, they are fully "adaptive": under the control of onboard supercomputers the size of a shoebox that are now being built (a spin-off from "Star Wars" research), they will be continually reprogrammed. This flexibility began a decade ago with modified parabolic antennas, and the trend will continue. Satellites of the 21st century will thus be able to "reuse" the same slice of spectrum many times over. Reuse will soon reach 100-fold on some satellites and should in time reach 1,000-fold.

We can expect phased arrays to become familiar on terra firma as well, because they can direct beams to satellites moving in known orbits overhead. In addition, these arrays can be constructed to conform to almost any desired shape, which makes them particularly attractive for aircraft and cars. Within the next five years we should even see miniature versions in handheld transceivers.

Competition from the Ground

The biggest economic hurdle for satellites in industrial countries will be competing with optical-fiber systems to provide high data-rate, or broadband, services directly to the home or office. A satellite system cannot match the transmission speed of a simple span of fiber-optic cable. In reality, however, most consumers rely on a mile or so of much slower paired copper telephone wires or coaxial cable to bring voice and data from a local distribution center.

This "last-mile problem," as it is known, is a major bottleneck for wired networks. Telephone companies have developed a way to increase data rates carried by cable and wires from tens of thousands of bits per second to a few million. Yet despite improvements in the price and performance of this technology, known as xDSL, it is still expensive and is unlikely to meet demand for broadband data.

Many home users of the World Wide Web, for example, are frustrated by delays fetching graphics. A broadband Internet connection transports data 50 times faster than a typical 28.8-kilobit-per-second dial-up telephone connection; high-definition television swallows bits at rates 20 to 30 times faster still. Many users will want multimegabits of data per second by halfway through the next decade. Consequently, satellites have perhaps a 10-year window of opportunity in the multimedia marketplace.

The coming renaissance of satellite systems was not always obvious. In 1993 Nicholas Negroponte of the Massachusetts Institute of Technology suggested that the future of telecommunications would be a huge flip-flop. Narrowband services, telephone and paging services that are now often carried long-distance by glass fiber would migrate to wireless transmission. At the same time, cost and the limited amount of available radio spectrum would force broadband services to migrate in the opposite direction, from radio waves and satellites to fiber optic and coaxial cable. This became known as the Negroponte Flip.

TELECOMMUNICATIONS SATELLITE of the next century will have two phased-array antennas, seen as hexagonal structures in this example (*right*), for transmitting and receiving signals in numerous narrow "spot" beams. Solar panels (*long rectangular shapes*) provide power for onboard electronics, including powerful processors that control the antennas and handle thousands of separate voice or data links. This satellite is in medium earth orbit, about 10,300 kilometers (6,400 miles) high.

In a dissenting article in *Telecommunications* magazine, I argued that Negroponte was wrong. The future would feature a "rich but confused" digital mixture of fiber, coaxial cable, terrestrial wireless and satellite services carrying everything from voice to broadband multimedia and video services. In this scenario, users would demand access from mobile terminals to broadband services as well as to less demanding narrowband ones. Glass fiber, satellites and terrestrial wireless networks would, I suggested, each be important in the mix, and protocols for seamless interconnection between these would become the technical crunch point.

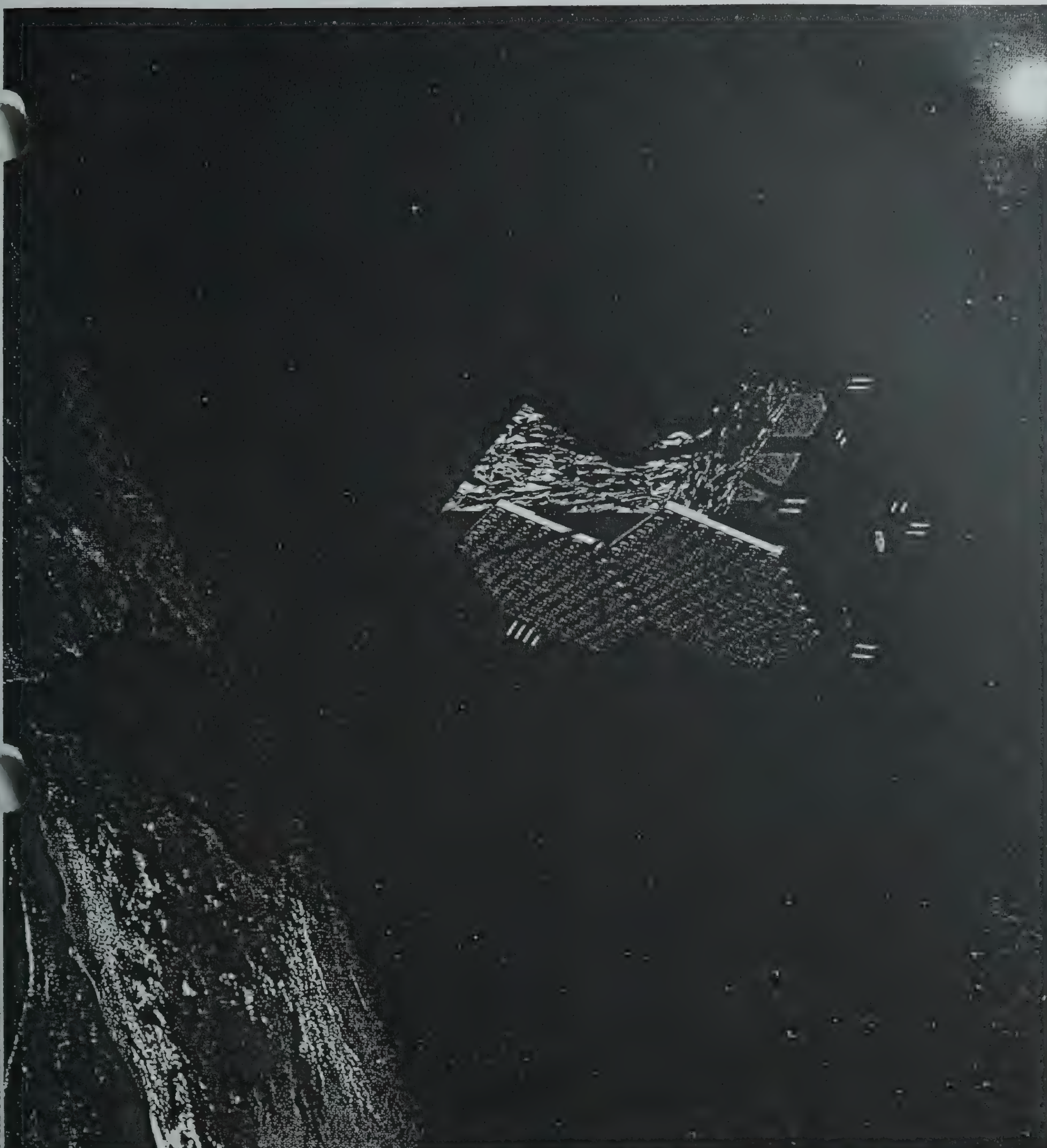
Telecommunications dubbed this view the Pelton Merge. If correct, it meant that engineers would face the challenge of developing broadband satellite-based services that could be interconnected with glass fiber and coaxial cable-based systems. It followed that the next generation of communications satellites would have to be 1,000 times faster than even those of the early 1990s. And there would be an urgent need for new data-conversion protocols and "open systems" standards, specifications that manufacturers could use to build compatible new devices.

Breakthroughs in satellite technology are making the merge model increasingly credible. During the past five years, wireless services and satellites have been experiencing record growth. Today they can provide a telephone-line transmission at a cost below 0.1 cent a minute. Moreover, the most rapidly growing type of telecommunications service is direct broadcast satellite (DBS) television, which uses geosynchronous orbiters to beam signals to more than 20 million subscribers worldwide. Market studies have projected the total could triple by 2005. Yet according to the Negroponte Flip, television should be carried by cable.

Exploiting a Finite Resource

Satellites still face significant technical obstacles. A crucial one is the extremely high cost of launching a payload and insuring it. There is an urgent need for innovative ways to put equipment into orbit reliably and at much lower expense. New launch concepts are being investigated, including reusable rockets and jets. So far, though, none has proved itself.

Other challenges stem from the need to make the most efficient use of the finite radio spectrum. All modern systems transmit information in digital form. One important approach is to compress data digitally. DBS, for example, benefits from a new Motion Picture Experts Group standard, MPEG2, which allows transmission of high-quality video images to home TV screens using only six megabits per second. This now enables a one-gigabit-per-second DBS satellite such as



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DirecTV to transmit over 150 television channels plus many CD-quality audio channels. Some mobile systems compress voice data for the same reason.

Because high frequencies can carry more data than low ones, the bands used for wireless have steadily increased in frequency from tens of megahertz midcentury to almost 100 gigahertz in today's most ambitious schemes. But transmitting and processing thousands of signals takes considerable power—a scarce resource on satellites. It is a particular challenge for GEO satellites, which must cope with very large numbers of beams and transmit them 40,000 kilometers.

Power is also a challenge for satellites offering mobile services, because the small antennas now used in portable transceivers intercept only a tiny fraction of a satellite's signal. That increases the power and sensitivity required of the satellite. As a result, the typical solar array on a geosynchronous satellite has increased in power from around two kilowatts to more than 10 kilowatts over the past five years. This trend has been achieved partly through the use of larger solar arrays and partly by higher efficiency. Solar cells made of new materials, such as the combination of gallium arsenide and germanium, have reached efficiencies of about 23 percent, twice the figure for amorphous silicon.

Solar concentrators that reflect light so as to expose cells to

more radiation, together with multijunction devices that capture infrared and ultraviolet as well as visible light, could push efficiencies above 30 percent in the next five years. Flexible solar arrays capable of generating 60 kilowatts or more are a distinct possibility for the future, and improved fuel cells and high-performance batteries will also help.

High data rates necessitate large antennas, especially for GEO systems. Parabolic satellite antennas 10 meters in diameter can now be built, and it should be possible to extend that to 20 or 30 meters. So far the most ambitious phased-array satellite antenna is on the Japanese Gigabit Satellite. The antenna this satellite will use to receive signals is some three meters in diameter and will be made up of 2,700 cells or individual antenna elements. Larger antennas with tens of thousands of cells may become feasible as designers gain experience and manufacturers learn how to mass-produce the devices at low cost.

To win mass-market acceptance, however, service providers will need to bring the cost of ground terminals to the lowest possible levels. Better designs and the adoption of large-scale manufacturing techniques should help achieve this end. Some DBS terminals are now only 30 centimeters in diameter, and their price is falling to below $200. In the future, gallium arsenide–based phased arrays are likely to help reduce antenna costs in space and on the ground.

Location, Location—GEO versus LEO

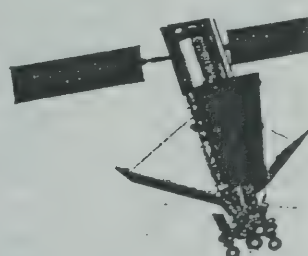
Most communications satellites today are in GEO. Starting with the International Telecommunications Satellite Organization (Intelsat) in 1965, most of them have communicated with fixed ground stations. Over a decade ago, the International Maritime Satellite Organization (Inmarsat) pioneered mobile telephony and data links for ships, and within the last year, American Mobile Satellite Corporation and Telesat Mobile in Canada have introduced similar services in North America for land-based mobile users. By building satellites with bigger antennas, these companies have reduced costs, but their services have suffered because of transmission difficulties (and poor marketing).

The engineering challenges of geosynchronous satellites account for the surge of interest in recent years in systems using satellites in LEO, at an altitude of less than 1,600 kilometers, or MEO, at 10,000 to 16,000 kilometers. (The intervening zone is avoided because the Van Allen radiation belts threaten the operation of satellites there.)

LEO systems, besides being faster than GEO systems, can be used with smaller terminals, because the satellite is typically 40 times nearer the earth. Three new LEO and MEO global land-mobile systems—Iridium, ICO (ICO Global Communications) and Globalstar—are scheduled to start offering telephony and global paging within a year or two, with Iridium first off the blocks.

The disadvantage of LEO and MEO systems is that satellites close to the earth move across the sky in an hour or two, rather than seeming to remain at a fixed point. For good reception, users must always be able to see at least one satellite that is well clear of the horizon, because a steep "look angle" minimizes losses caused by buildings and trees. This requirement explains why MEO and LEO systems have to employ so many satellites in order to provide continuous global coverage—around 60 for LEO networks. Launching and building the multiple satellites costs billions of dollars, and stringent precautions will be needed to ensure that abandoned satellites and orbiting launch debris do not become a danger.

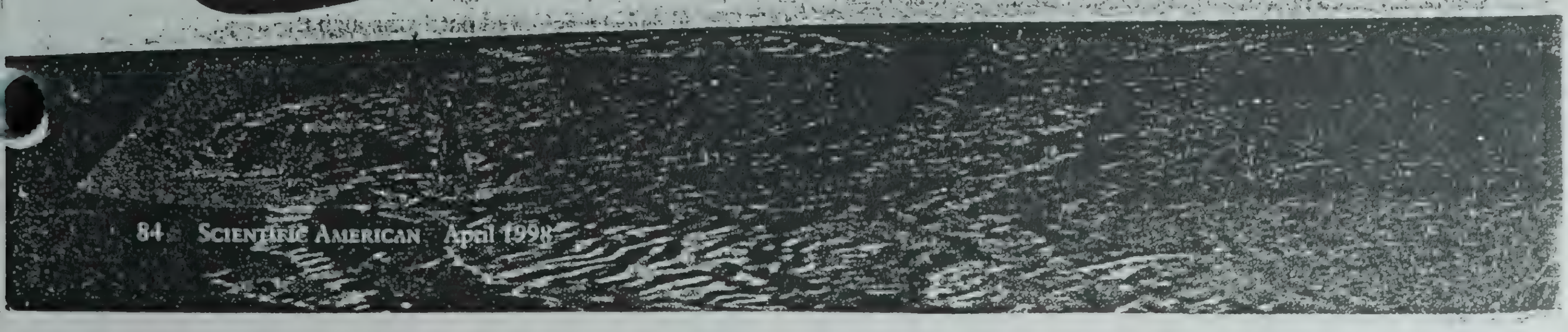
To offer affordable broadband services—such as interactive multimedia applications—via desktop antennas, satellite systems will have to employ the very highest frequencies, over 20 gigahertz. Even with the extensive reuse of frequencies made possible by phased-array antennas, these systems will need large slices of spectrum. Several broadband LEO and



LOW-EARTH-ORBIT satellite zooms only several hundred kilometers above the earth and will link users separated by comparable distances with very little delay. Many such satellites are needed, however, to cover the earth.

SLIM FILMS

HIGH ALTITUDE LONG ENDURANCE (HALE) platforms in coming years will hover 20,000 or more meters above the earth; they will link mobile users up to 500 kilometers apart. Some may be dirigibles, whereas others will have wings and fly like conventional aircraft.



SATELLITE in geostationary orbit some 40,000 kilometers above the earth can link mobile users many thousands of kilometers apart, but data are delayed for a quarter of a second by the long round-trip.

MEO systems are now in development, notably Bill Gates and Craig McCaw's Teledesic, Alcatel's Skybridge and Motorola's Celestri (LEO-GEO hybrid). Various consortia have proposed at least a dozen other broadband multimedia networks, most of them GEO systems. These networks would employ massive power systems to blast their signals down to microterminals, although not all of them will be built.

Tomorrow's Technologies

The high cost of broadband multisatellite systems accounts for the growing enthusiasm for HALE platforms. These craft can be launched at moderate cost, and they can be called back for servicing. Studies indicate that such platforms could support phased-array antennas with some 3,500 beams, making feasible not only mobile two-way communications but also video distribution in an area 500 kilometers across. These systems will have to reuse frequencies 100-fold, and they will talk to satellites to make global connections.

Four basic types of HALE platforms are being discussed: helium-filled, robotically piloted dirigibles stabilized by ion engines; units powered by solar or fuel cells; piston-driven platforms; and jet engine–driven platforms. These approaches face contrasting limitations: fuel- and solar-cell-powered platforms will be hard-pressed to muster enough power, but piston- and jet-powered types will stay aloft only a few days.

Another way to provide broadband services is to move to frequencies so high that less reuse is needed. Unfortunately, there is an obstacle: rainy weather. The highest-frequency satellite systems now contemplated utilize wavelengths comparable to the size of raindrops. The droplets consequently act as lenses, bending the waves and distorting the signals. This effect can be mitigated by error-correction techniques, by using more power when necessary and by employing more ground terminals (so data can follow diverse paths). These measures, however, come at a price.

Moving to wavelengths below a millimeter presents even more obstacles. Infrared and optical beams—the logical next step—are easily absorbed in the atmosphere, so in the near future they will probably be restricted to use within buildings. But experiments carried out with the Japanese Engineering Test Satellite VI in the mid-1990s have revived hopes that communicating with satellites via laser beams might one day be feasible. A laser-based network would most likely carry only very heavy streams of traffic and would rely on multiple ground stations to minimize losses incurred by bad weather.

What is clear is that wireless systems will become more dominant over the next 20 years and that they will be based on a mixture of technologies. Universities, government and industry all have roles bringing these schemes to fruition. Unfortunately, there are very few courses of study in the U.S. or in other industrial countries to train students to tackle the emerging issues.

One possibility that deserves serious consideration is to establish a global institute that would foster the requisite expertise. I and several others are now investigating the feasibility of such a plan. But even if such an institute is established, a shortage of suitable scientific and engineering skills may still be an important barrier to progress. More solutions are needed, because the benefits of better communication and education are immense for all nations. SA

The Author

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Further Reading

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CELLULAR TOWERS (*small structures on ground*) can serve regions a few kilometers across. Some systems will combine satellite and terrestrial cellular technologies.

Terrestrial Wireless Networks

Seamless switching between networks will draw users to wireless data services. A working model is now in operation

by Alex Hills

In the past decade, cellular phones have gone from being a rarity to being commonplace. More than 50 million Americans, one in five, use these devices; one in six uses a wireless pager. In developing countries where standard telephone service is not universally available, cellular is often seen as a better alternative to conventional wired service, because wireless systems can be built quickly. Clearly, if a communications service can be made portable, convenient and affordable, demand is great.

Consumers and businesses have been much slower to adopt wireless systems for data communications than for telephone service. (Paging barely scrapes the surface of wireless's potential.) In the U.S., data communications have been estimated to account for only 3 percent of wireless traffic with mobile terminals, and the proportion is probably even less in most other countries. One explanation for this imbalance between voice and data services is that wireless telephone service has been available to consumers for longer than wireless data—since the early 1980s. And long before that, people in industrial countries were already accustomed to using telephones. Widespread use of computers, in contrast, is fairly recent, and

so applications for wireless data links are much less mature.

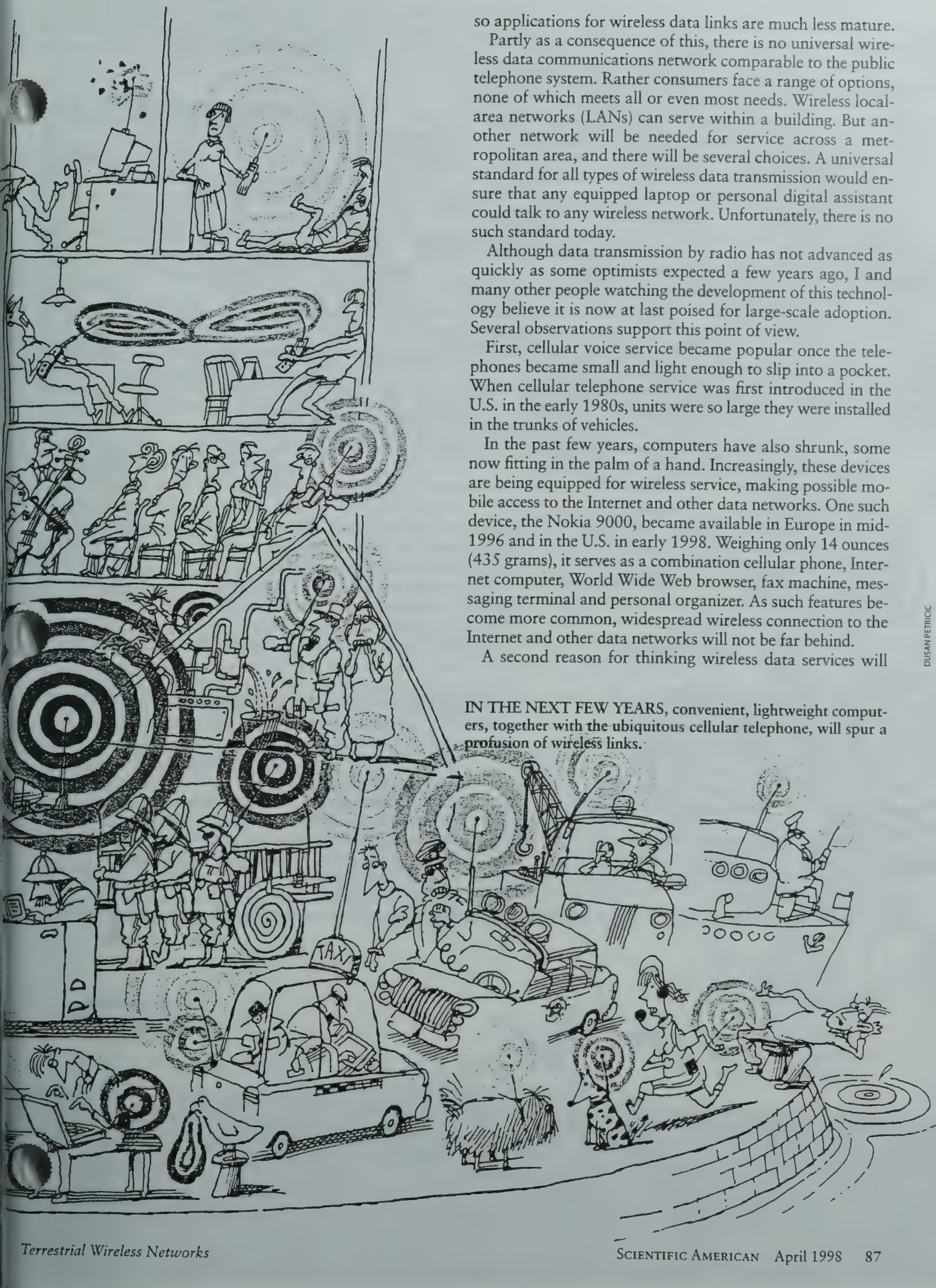
Partly as a consequence of this, there is no universal wireless data communications network comparable to the public telephone system. Rather consumers face a range of options, none of which meets all or even most needs. Wireless local-area networks (LANs) can serve within a building. But another network will be needed for service across a metropolitan area, and there will be several choices. A universal standard for all types of wireless data transmission would ensure that any equipped laptop or personal digital assistant could talk to any wireless network. Unfortunately, there is no such standard today.

Although data transmission by radio has not advanced as quickly as some optimists expected a few years ago, I and many other people watching the development of this technology believe it is now at last poised for large-scale adoption. Several observations support this point of view.

First, cellular voice service became popular once the telephones became small and light enough to slip into a pocket. When cellular telephone service was first introduced in the U.S. in the early 1980s, units were so large they were installed in the trunks of vehicles.

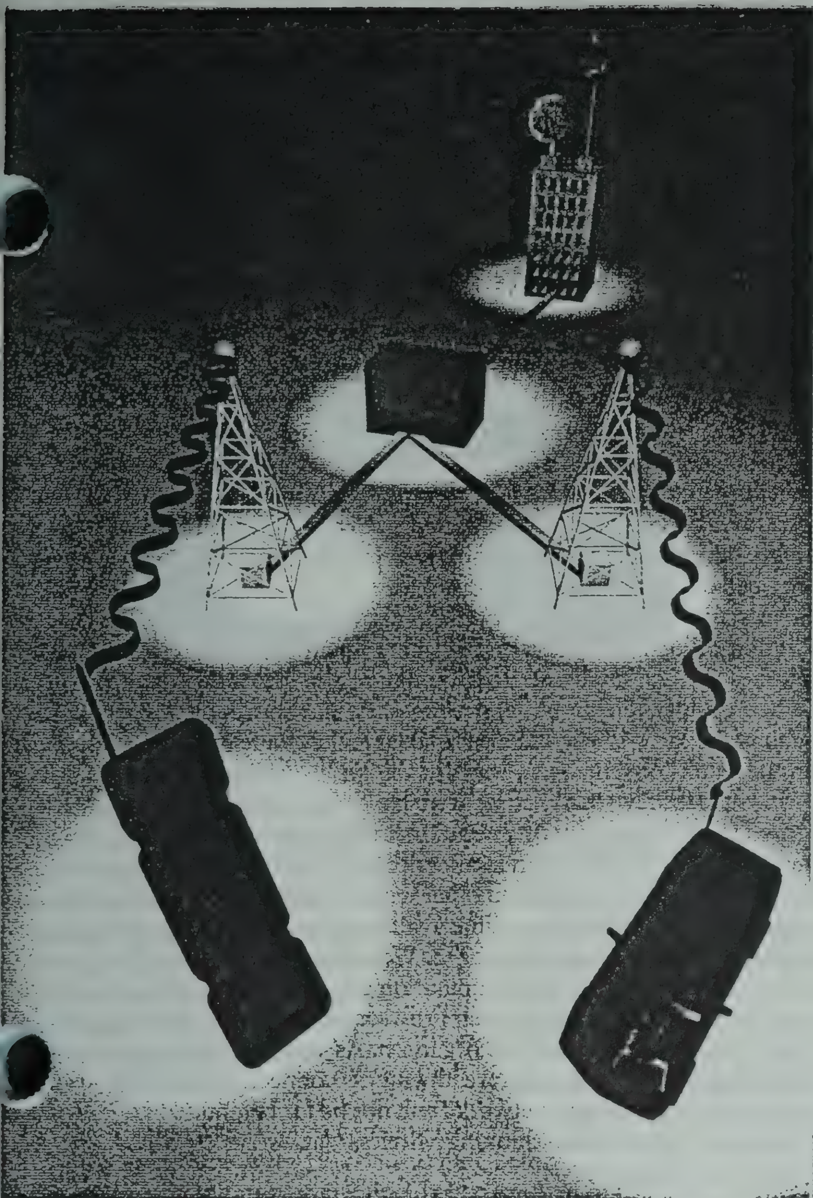
In the past few years, computers have also shrunk, some now fitting in the palm of a hand. Increasingly, these devices are being equipped for wireless service, making possible mobile access to the Internet and other data networks. One such device, the Nokia 9000, became available in Europe in mid-1996 and in the U.S. in early 1998. Weighing only 14 ounces (435 grams), it serves as a combination cellular phone, Internet computer, World Wide Web browser, fax machine, messaging terminal and personal organizer. As such features become more common, widespread wireless connection to the Internet and other data networks will not be far behind.

A second reason for thinking wireless data services will



IN THE NEXT FEW YEARS, convenient, lightweight computers, together with the ubiquitous cellular telephone, will spur a profusion of wireless links.

DUSAN PETRICIC



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CELLULAR NETWORK connects users (*red car* and *portable telephone*) via radio links to individual cell sites (*yellow towers*), usually a few kilometers apart. Adjacent cell sites use different frequencies to avoid interference. The cell sites are connected by fiber-optic cables to a mobile telephone switching office (*blue*), which "finds" call recipients and maintains active connections (*purple*). The mobile office is in turn connected to a public telephone service exchange (*green*), through which calls can be routed anywhere in the world by satellite, cable or microwave links.

flourish is that the Institute of Electrical and Electronics Engineers, an influential U.S. professional organization, adopted a standard for wireless LANs in June 1997. Although this standard, called IEEE 802.11, does not cover systems other than LANs, it should encourage manufacturers worldwide to build equipment that can connect with many different wireless LANs, not just with their home systems. The standard provides for operation with two different transmission techniques, but consumers might gravitate to one of them and so establish a de facto standard that will in coming years become very widely used.

A third reason for confidence is that a successful working model of a high-speed, user-friendly, campus-scale wireless data system already exists. Some colleagues and I have built a network that services about half the campus of Carnegie Mellon University and links seamlessly to a slower commercial metropolitan network. Users can move about freely with their mobile computers (usually laptops) and work with them as they would desktop machines. (I describe this system in more detail later.)

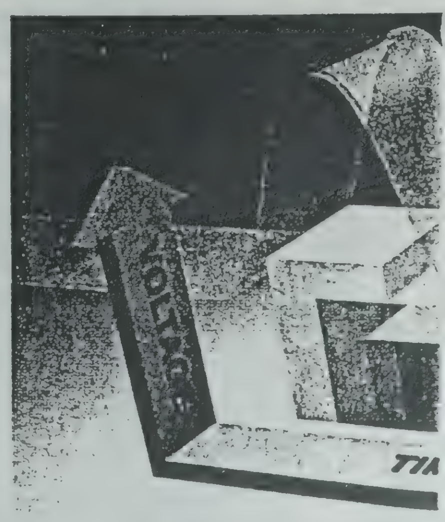
Wireless data services will never eliminate the need for wired connections. Some of the emerging applications for interconnected computers, such as video and multimedia, require extremely high rates of data exchange. Inherent physical limits restrict the maximum speed of wireless links, so the fastest connections will probably always be wired. Further, because wireless networks always require the support of a wired infrastructure as well as the transmitting and receiving equipment, they are normally more expensive than wire-only networks. But where mobility is valued, wireless links will become an increasingly attractive option.

Wireless systems are usually designed around fixed transmitter-receiver base stations that communicate with portable sets as well as with a wired network, often the public telephone system. Wireless voice networks range from cordless telephones to global satellite systems. In between are wireless private branch exchanges, which provide service within a building or campus, and cellular and personal communications service (PCS) systems, which serve a city-size area.

Similarly, data systems range from wireless LANs, which typically operate at about two megabits a second, to satellites. Paging networks and two-way "packet radio" networks, such as Ardis and RAM Mobile Data, provide slower wireless data service, up to 19.2 kilobits a second, over metropolitan or larger areas. (Packet-based networks are so called because they break a data stream into discrete packets that are "addressed" to the intended recipient.) These networks are often utilized by industries whose workers move about frequently.

Keeping the Signals Straight

Perhaps the most difficult challenge for a wireless designer is minimizing interference caused by radio noise and signal reflections. Because the batteries in mobile units have to be lightweight, systems must be designed to allow clear reception from mobile sets transmitting with less than half a watt of power. They must do this even though the radio sig-



MULTIPATH EFFECTS can distort a digital signal through "delay spread." Signals that reflect off buildings and terrain produce data bits that arrive at the receiver later (*purple* and *orange blocks*) than do the bits in a direct signal (*yellow blocks*), because their path from the transmitter is a little longer. The delayed data bits add to the direct-path bits to produce a distorted aggregate signal (*green ribbon*), which the receiver may misinterpret, resulting in a data error.

nals have to pass around obstructions. People want to use their sets wherever they happen to be, and that is often in the canyons between tall city buildings, for example.

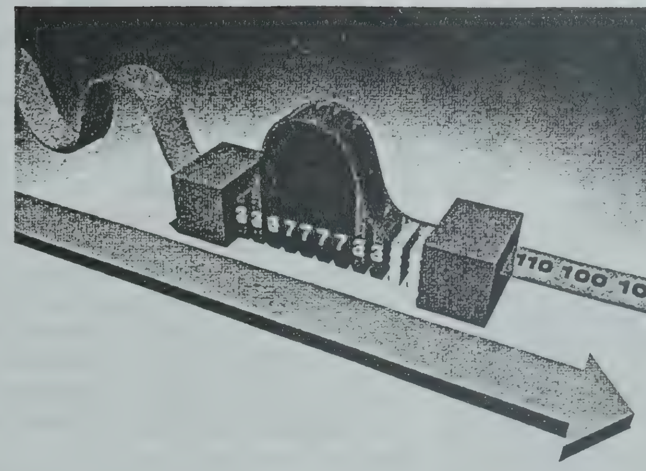
Radio signals reflected by buildings, vehicles and terrain cause a troublesome phenomenon called multipath fading. Depending on the lengths of the different paths, the deflected signals may partially cancel out the main signal. To make matters worse, the effect varies with frequency and changes as the mobile terminal moves around. Multipath fading can sometimes be heard on a car's FM radio: the signal fades in and out rapidly as you drive along.

Until a few years ago, cellular telephone systems employed analog technology, transmitting a continually varying signal just like an FM or AM radio station. In more modern digital systems, the analog voice signal is first converted to a stream of binary bits at the transmitter. Typically, the signal is sampled 8,000 times per second, and then each sample is converted to an eight-bit binary number. The resulting sequence of 64,000 bits per second is often "compressed," reducing the number of bits that must be sent. At the receiver the bit stream is converted back to the original voice signal.

A digital receiver can interpret an incoming bit only as a 1 or a 0. The absence of middle ground reduces the chance of a transmission error. Multipath effects, however, can give rise to a characteristic problem called delay spread, in which data are "smeared out" in time. This distortion is often what limits the reliable speed of a wireless link.

Uncorrected bit errors could be disastrous during transmission of a computer program or vital data. But digital transmission offers good opportunities for eliminating errors. Usually some error-correction bits that depend on the identity of nearby data bits are added to a transmitted sequence. The receiver evaluates these special bits, and because it "knows" what rules are in force for generating them and what types of data corruption are most likely, it can often correct discrepancies. This technique rectifies the large majority of bit errors.

Another digital technique to combat noise and multipath fading, commonly employed in wireless LANs, is known as spread spectrum. Often used in combination with error-correction coding, it takes advantage of the tendency of multipath fading and noise to vary with frequency. Spread-spec-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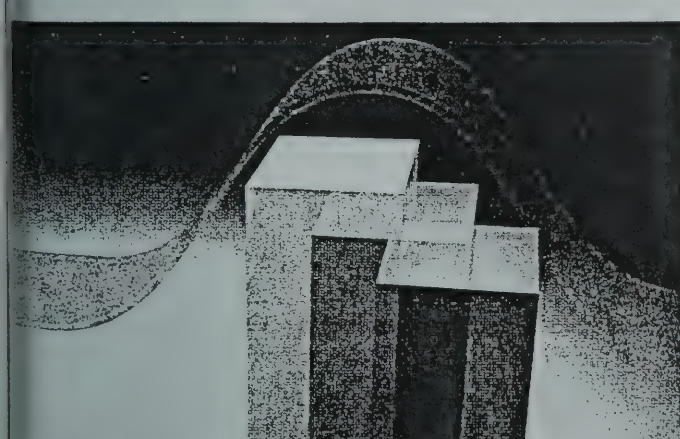
MODERN TELECOMMUNICATIONS SYSTEMS convert a voice signal to a string of binary data bits before sending it long distance. An analog voice signal (*pink ribbon, left*) is measured thousands of times per second, and the result is expressed as a number (*vertical bars, center*). The numbers are then converted to groups of 1s and 0s (*pink ribbon, right*)—which commonly include eight bits each, rather than the three illustrated.

trum techniques deliberately spread the transmitted signal over a broad range of radio frequencies. The message is then almost certain to get through on at least some of them.

In one spread-spectrum technique, referred to as frequency hopping, the transmitter switches to a new frequency every few milliseconds. The receiver knows the sequence and follows along. Even if some frequencies do not work, others will. With data communications, the receiver can request retransmissions of corrupted data, so that the correct message can be reassembled.

Another spread-spectrum technique is called direct sequence. With this technique, each data bit is converted to a series of several transmitted bits (or chips). The sequence of chips looks random but is known to both transmitter and receiver. So a data bit 1 might be converted to the chip sequence 000100110101111 and a data bit 0 converted to the inverse sequence, 111011001010000, which is readily distinguished from the first one. Because this operation generates more bits per second than it starts with, the resulting signal spreads over a wide range of frequencies when it is transmitted, minimizing interference and multipath fading. The receiver can then reconstruct the original data with high fidelity.

To make an (imperfect) analogy, a person who is hard of hearing might misunderstand me if I say the word "hallelujah." But if I hire a choir to sing the "Hallelujah Chorus" from Handel's *Messiah*, the message will probably get across, because the music repeats the word many times at frequencies from soprano to bass.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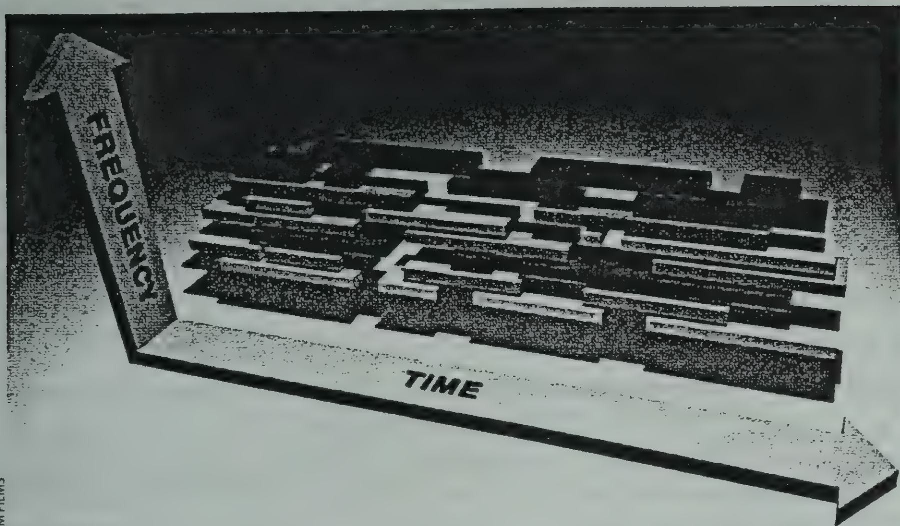
A Voice in the Crowd

For the wireless designer, almost as problematic as eliminating errors is allowing as many users as possible to share scarce radio spectrum. Many wireless networks rely, for this purpose, on the principle of frequency reuse. Cellular telephone systems, for example, divide all available radio channels into subsets. Only one subset serves in each cell site. Geographic spacing between cells that have the same subsets



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SIMPLEST TECHNIQUE to allow multiple users (*colors*) to communicate over the airwaves is to assign each user a different frequency, a procedure called frequency division multiple access (FDMA). Receivers are programmed so they know which transmitter operates on each frequency. By tuning to different frequencies—different heights in this illustration—the receiver can separate the signals from various users, much as a listener tunes in to different stations on a radio dial. Individual signals are shown as intermittent, because channels are not in continuous use.

reduces interference and allows the same frequency to be employed many times over in separated regions. PCS and digital cellular systems operate on a similar principle.

The capacity of a cellular network can be increased further by employing "microcells" half a kilometer or so in radius, rather than the typical "macrocells," which are usually more than two kilometers in radius in the city and can be much larger in rural areas. Though not yet in widespread use, microcells offer an attractive way to bring telephone and data service to underserved areas, particularly in densely populated regions of developing countries.

Base stations use several methods to keep separate the signals from different mobile units. Traditionally, this has been done using frequency division multiple access (FDMA), in which each mobile device sends on a different frequency. The base station knows which mobile is on which frequency and sorts out the signals just as one chooses a favorite FM or AM station, by tuning to the right place (a unique frequency) on the dial.

Digital technology makes possible schemes that allow multiple users to share the same frequencies. In time division multiple access (TDMA), favored by AT&T Wireless Services, each mobile set is assigned a repeating time slot a fraction of a millisecond long in which to transmit and to receive. The base station knows which mobiles are transmitting in which time slots; thus, it can keep their signals separate.

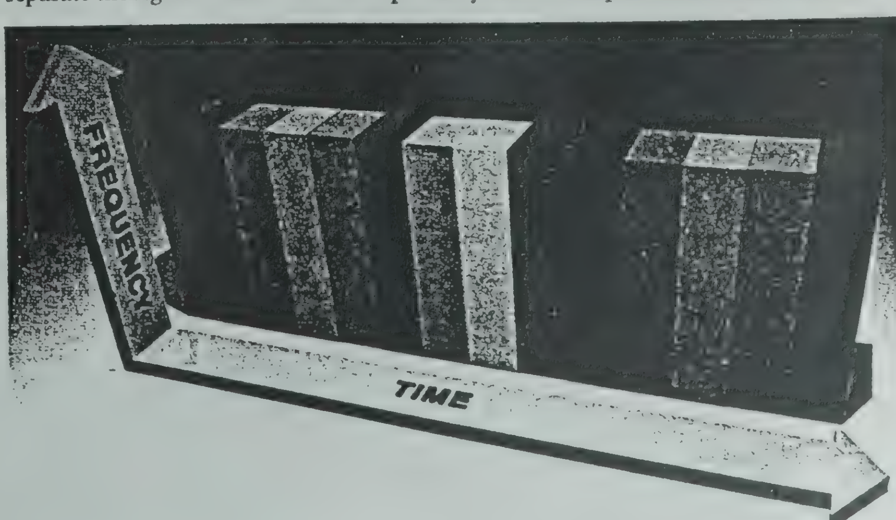
A rival technique pioneered by Qualcomm and used by U S West and Bell Atlantic—code division multiple access (CDMA)—is a little like direct-sequence spread spectrum in its mechanics. But the spreading sequence that replaces each data bit is much longer—more than 100 chips, as opposed to about 10. Moreover, the sequence is unique to the mobile station transmitting or receiving it. This feature allows multiple users to transmit at the same time.

The base station checks the aggregate of the incoming spread-spectrum signals to determine how well it correlates with each mobile unit's spreading sequence and, on this basis, determines which data bits were sent by each mobile. Many cellular and PCS companies have now adopted CDMA, which is typically combined with FDMA. To facilitate the transition to new bands and the new multiple-access techniques, some wireless carriers simultaneously operate both old and new systems and provide their customers with multimode sets.

All these technical innovations expand the potential for wireless communications. In developing countries the most urgent need is usually simply for reliable telephone service. This basic capability makes trade more efficient and enhances overall health and safety by allowing people to summon help quickly. Wireless communications can provide this service with minimal heavy construction and low initial investment: capital requirements, at $200 to $500 a line for a microcellular system, are less than half those of laying a cable network. Once installed, however, wireless systems can be fairly easily adapted for data transmission if demand grows.

Studies that Hung-Yao Yeh, also at Carnegie Mellon, and I have done indicate that wireless manufacturers will, however, need to make more frequency channels available through their equipment to exploit the full potential of wireless systems in the nonindustrial world. We have also concluded

ALTERNATIVE SCHEME for allowing multiple users to share radio spectrum is time division multiple access (TDMA). Each user (*colors*) is assigned a repeating time slot a fraction of a millisecond in length (*vertical bars*). Digital data from each user are compressed in time and sent at high frequency within that user's time slot. The receiver can separate the signals because it knows precisely when to expect each of them.



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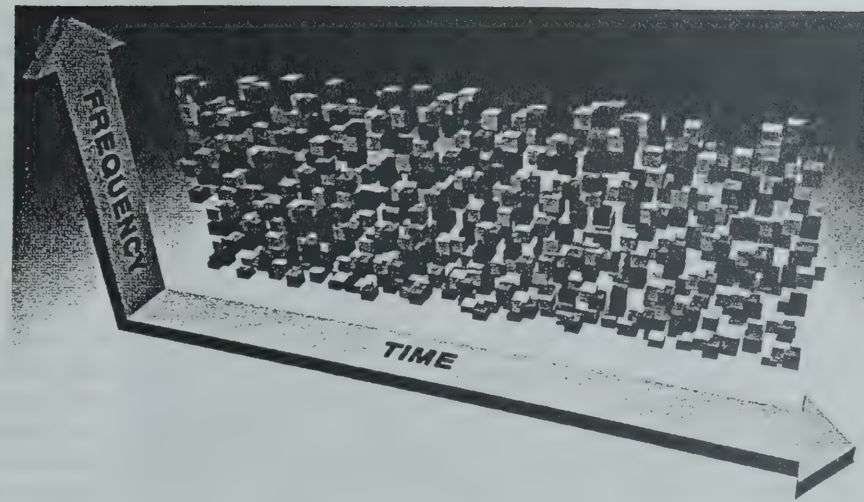
that, given the benefits to be expected from telephone service, national governments should make more radio spectrum available for wireless systems.

A Working Model

One development that would most likely encourage wider use of wireless networks for data communications would be seamless switching between networks. A consumer could then have uninterrupted access to the Internet or other data networks without being concerned about the peculiarities of the underlying wireless system.

At Carnegie Mellon, Bernard J. Bennington, Charles R. Bartel, Peter W. Bronder and I, among others, have created a test bed for seamless switching that includes a wireless LAN and a cellular-based metropolitan-area network. As far as we know, it is the biggest wireless LAN installation anywhere. Operating with equipment made by Lucent Technologies, it now has more than 100 base stations and provides data services at speeds of two megabits a second to about one half of the campus area.



COMPLEX SCHEME is made possible by coding; code division multiple access (CDMA) allows multiple users (*colors*) to share radio spectrum efficiently without assigning them individual frequencies or time slots. Each user's signal is encoded in such a way that it "spreads" across the radio spectrum—vertically in this illustration. Spreading ensures that individual users' signals do not obliterate one another. The receiver distinguishes the jumble of individual spread signals by their unique codes.

As users move around the site, they can access the Internet and other networks from laptops or other portable machines while specific wireless connections are handled automatically. Popular applications include checking e-mail and accessing the Internet. The mobile computer becomes as effective as a wired desktop machine—but more convenient. We plan to extend service to the entire campus community by 1999.

Off-campus operation is also possible in the greater Pittsburgh area through the Cellular Digital Packet Data (CDPD) service offered by Bell Atlantic Mobile. This service, however, operates at only 19.2 kilobits a second.

Among the challenges we faced was that as a user moves about, his or her machine needs to maintain the best connection for its current location and task. This requirement sometimes means that the connection must be "handed off" from one network to another. My colleague David B. Johnson has written software that allows these handoffs to take place in a way that is not noticeable to the user.

Because many computers work in a client-server model, in which data files must be moved around, access to distributed files also requires special attention in a wireless network. Radio links function at lower speeds than wired links and produce more bit errors. Furthermore, they can fail from time to time. Distributed file systems for use with a wireless network must be designed to tolerate these imperfections. Mahadev Satyanarayanan, also at Carnegie Mellon, has been working on ways to build such file systems.

Another colleague, Daniel P. Siewiorek, builds the mobile computers themselves. He and his associates have assembled a whole series of wearable computers. These devices are convenient for a variety of purposes, ranging from navigation to providing instructions for people constructing aircraft. Many of Siewiorek's wearable computers (and similar ones devised elsewhere) are equipped for wireless, and we hope one day the vision of seamless and ubiquitous wireless connectivity will be achieved using these machines.

We have thus achieved our vision of seamlessness with wireless LANs and metropolitan-area networks. A laptop computer equipped for both can move freely from one coverage area to the other while maintaining a continuous connection. We expect that comparable systems will be installed elsewhere. These prototypes should eventually link up with satellites and other systems to form a user-friendly, international wireless data-transmission network. SA

The Author

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Further Reading

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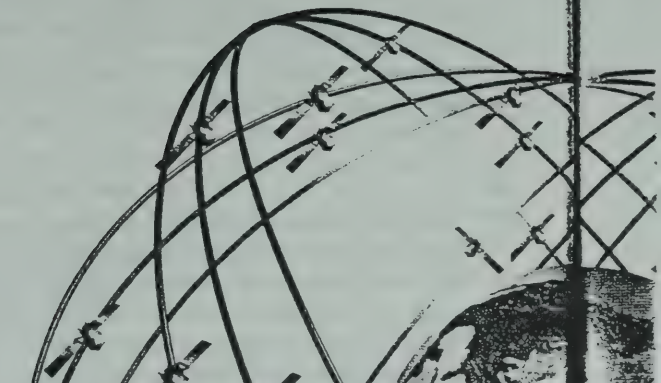
Moving beyond Wireless Voice Systems

Cell phones are but one application of wireless communications. The technology also enables accurate position determination and the monitoring of remote sites

by Warren L. Stutzman and Carl B. Dietrich, Jr.



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Over the next few decades, the increasingly integrated network of terrestrial and satellite-based radio systems will grow to meet the rising demand for fast, mobile communications. Desire for simple wireless conversations first spurred the construction of this infrastructure, but many other uses are emerging. Primary among these are capabilities for determining the position of a person or object and for monitoring devices at a distance.

Until recently, such applications might have sounded as though they would be helpful only to professional navigators, surveyors or technicians. But wireless technology is so versatile—and the systems so compact and inexpensive because of advances in electronics and computing—that it can benefit even routine aspects of daily life, such as driving across town or protecting a house from burglars.

Years ago the only navigational aids were the stars and systems that relied on gyroscopes. More recently, ground-based radio transmitters, such as those in the LORAN (LOng RAnge Navigation) network, have been used for position determination, but such systems suffer from a limited coverage area, and they do not give altitude information. Today, thanks to advanced satellites, people can determine their three-dimensional locations with amazing accuracy.

Perhaps most well known is the Global Positioning System (GPS), which consists of 24 satellites that circle the earth at an altitude of more than 20,000 kilometers (12,000 miles) in six orbital planes [see "The Global Positioning System," by Thomas A. Herring; SCIENTIFIC AMERICAN, February 1996]. The satellites continuously broadcast signals that can be "heard" from every point on the globe at any instant. By measuring when the timed digital transmissions arrive from at least four of the satellites (which indicates the distance to those satellites), a receiver can apply geometric principles to pinpoint its own location to within 18 meters (20 yards). The accuracy can be improved to less than one meter over a specific area when a transmitter at a known fixed location supplies additional information for fine-tuning the calculations.

The first dramatic use of GPS came during the Persian Gulf War, when troops relied on the technology to find their way in the Iraqi desert. Since then, commercial use has quickly become widespread. A few of the many applications include navigation, mapping and surveying, particularly in remote areas. Perhaps the most notable example is new cars equipped with GPS that can assist motorists in finding specific addresses. The technology is now even available to hikers in the form of handheld devices costing as little as $100.

Because GPS provides three-dimensional position information, airplanes can use the technology to fly more direct courses, rather than following dense traffic lanes between land-based radio beacons. In addition, the extreme accuracy of GPS may one day render elaborate and expensive ground-based tracking radars unnecessary.

GPS has a Russian counterpart: the Global Navigation Satellite System (GLONASS). In 1995 the last of the GLONASS satellites were deployed, completing a full constellation of 24 spacecraft, but some have since become inoperable. Planned launches of at least nine additional satellites are expected by the end of this year.

When GLONASS becomes fully operational, it will significantly increase the performance of receivers that use both the Russian and GPS signals. The improvement will be especially noticeable in "urban canyons," downtown areas where tall

SATELLITES in the U.S.'s Global Positioning System (*blue*) and Russia's Global Navigation Satellite System (*red*) circle the globe and continuously broadcast signals that can be "heard" from every point on the earth. A receiver can use the timed digital transmissions to determine its location. Using GPS alone, people can pinpoint their own positions to within 18 meters (20 yards).

buildings and other obstacles interfere with the satellite transmissions. In addition, the proposed European Navigation Satellite System (ENSS), which calls for 15 satellites to cover Europe and Africa, could further refine the accuracy of position determination in those areas. Whereas other modern satellite and terrestrial services also provide location information, they charge fees, and none are as accurate.

With all their capability, however, systems such as GPS have one major shortcoming—they lack a return link. People with handheld GPS terminals know where they are, but nobody else does. Thus, many applications require the user to have a separate transmitter.

Position can also be determined with remote determination satellite service (RDSS), which is frequently used in conjunction with two-way messaging. RDSS works on the same basic principle as GPS but in reverse: a ground transmitter sends a signal that is then received by two or more satellites in the system. By measuring the different arrival times of the signal (indicating different distances traversed by the transmission), RDSS can use geometry to calculate the location of the terrestrial radio. One current RDSS application, designed for managing a fleet of trucks, can determine the location of a vehicle-based transmitter to within about 0.3 kilometer.

A future service will incorporate a two-way pager. The user would wear a device that receives request signals over a low-earth-orbit (LEO) satellite. The inexpensive pager transmits back through the satellite to a ground station that would then determine the pager's location. Such technology could be used to monitor the whereabouts of Alzheimer's patients or small children.

Ground-based wireless networks can also handle data transfers for various remote-monitoring jobs. New innovative services take advantage of idle cellular voice and control channels to broadcast messages, such as commanding a utility meter equipped with a transmitter to report a reading. Short message bursts are then sent back from the meter on the premises to a service center connected to the cellular grid. Another use is for monitoring vending machines that send a message when product inventories are low, thereby eliminating unnecessary site visits by distributors. A different application could issue an alert with the location of a railcar or truck that has a broken refrigeration unit so that any perishable items might be saved.

Wireless technology has been a blessing for applications in out-of-the-way locations. A petroleum company is now field-testing a cellular-based system for checking the corrosion of gas and oil pipelines in remote areas. Park officials at Death Valley National Monument are using a satellite-based network to monitor the water level of the Devil's Hole pool in Ash Meadow, Nev., the only known home of an endangered species of desert pupfish.

Alarm systems are an especially important application, not only for thwarting burglars but also for avoiding catastrophes. A future device will monitor railroad crossings, issuing a wireless alert when equipment malfunctions. A dispatcher can then immediately send a repair crew to fix the problem.

In some parts of the U.S., enhanced emergency 911 service responds quickly to telephone calls even when the people in distress are unable to give their location. Recently the Federal Communications Commission has required that cellular and personal communications systems also be able to provide a caller's phone number and, starting in October 2001, to locate a user to within 125 meters two thirds of the time. To avoid the cost of outfitting every telephone with a GPS receiver, ground-based position-location technology is currently being developed.

Future wireless systems for position determination and remote monitoring will continue to require ingenuity and creativity from their designers. The applications in use today are merely the beginning. SA

The Authors

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Spread-Spectrum Radio

Dicing information into digital bundles and transmitting them at low power over different frequencies can enable millions of people to send and receive simultaneously

by David R. Hughes and Dewayne Hendricks

Conventional wisdom holds that radio airspace is a valuable—and limited—resource that has to be rationed, like water in a desert. That mind-set comes from traditional transmitters and receivers, whose operation must be restricted to narrow, dedicated slices of the electromagnetic spectrum to minimize interference. Thus, governments have parceled out and licensed radio channels like real estate. In the U.S., the Federal Communications Commission (FCC) has sometimes used a cash-bidding process to allocate precious frequency bands for a variety of purposes, including commercial television and radio broadcasts; military, marine and police transmissions; taxi dispatchers; CB communications; and ham radio operators and cell phone consumers.

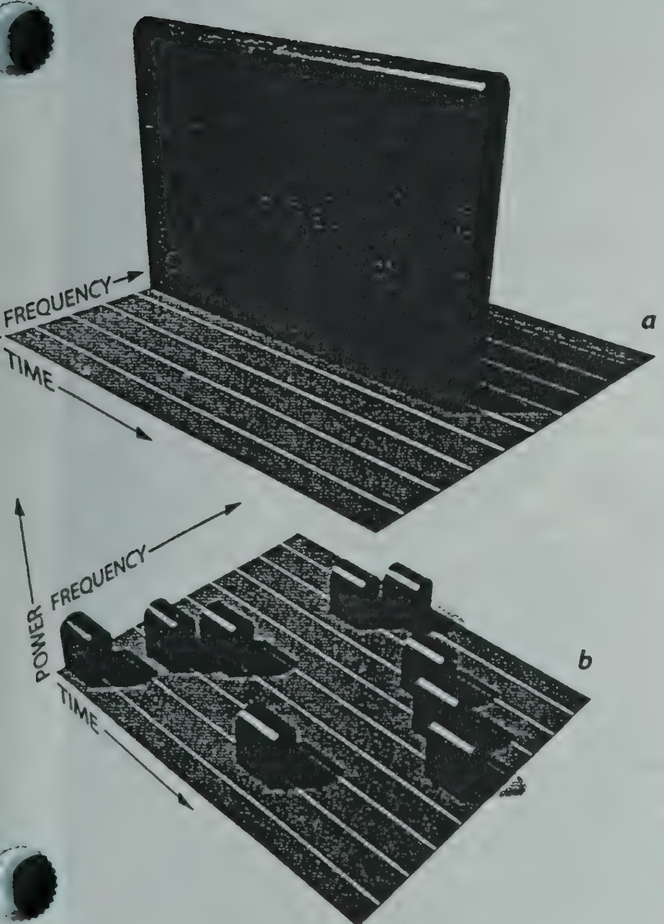
Recent advances in digital communications, though, have opened the door to an entirely new model. Transmitters can now deploy so-called spread-spectrum techniques to share channels without running afoul of one another. Information can be diced into tiny electronic bundles of 1s and 0s and then transmitted over radio waves, with each packet sent over different channels, or frequencies, at low power. New studies have shown that, theoretically, millions of radio transmitters within the same metropolitan area can successfully operate in the same frequency band while transferring hundreds of megabits of data per second.

Such shared use of the spectrum challenges customary practices. In the past, when allocating narrow frequency bands for exclusive commercial purposes, the government has granted licenses to firms, such as those offering cell phone and personal communications services (PCS). Those licensees charge consumers for services, just as conventional telephone companies bill their customers. In the new economic model, the middleman becomes unnecessary: consumers can communicate with one another directly and at no charge, even when they are kilometers apart and when myriad other people are using the same radio channels. This fundamental change has led to revisions in the regulatory policies of the U.S. and foreign governments, which have now designated certain frequency bands for free, unlicensed use of spread-spectrum radios by the public.

Enough Spectrum for Everyone

What is the basis of this technology revolution? Traditional radios work by broadcasting information over a single, narrow channel with high power. By operating in as skinny a sliver of the electromagnetic spectrum as possible, a transmitter thus makes room for other devices to operate in neighboring frequencies without interference. But radio engineers now know that the opposite way of transmitting data—by smearing, or spreading, information across a wider chunk of the spectrum at low power—is more efficient.

The concept is counterintuitive: instead of carving a pie into a finite number of small slices, the technology allows a larger sharing of the whole pie by permitting an all but unlimited number of individuals to take barely noticeable bites. Although spread-spectrum radios use more bandwidth than



RADIO SIGNALS (*shown in red*) have typically been transmitted continuously over a single, narrow frequency band at high power (*a*). Engineers now know that a more efficient use of the radio spectrum is to spread a signal over different channels at low power, as shown in a technique called frequency hopping (*b*).

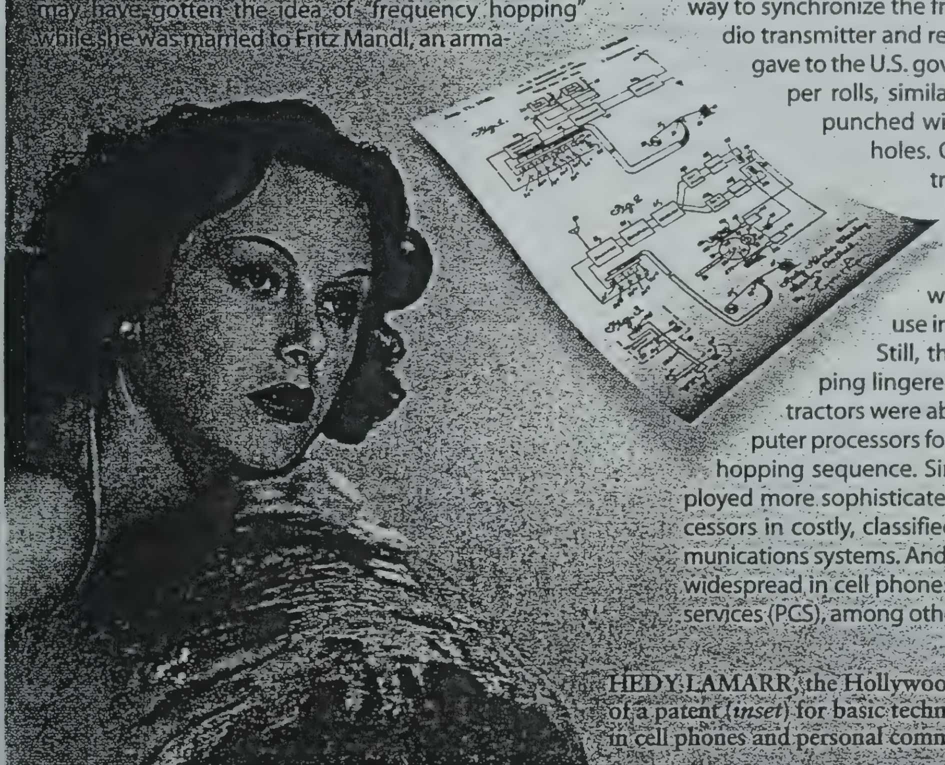
The Improbable Inventors of Frequency-Hopping Radio

She was gorgeous, glamorous and talented. And she had a mind for technology. In 1941 actress Hedy Lamarr, along with the avant-garde composer and musician George Antheil, filed for a patent to cover their "Secret Communication System," a device designed to help the U.S. military guide torpedoes by radio signals that would continually jump from one frequency to another, thus making enemy interception and jamming difficult.

Born Hedwig Maria Eva Kiesler in Vienna, Austria, Lamarr may have gotten the idea of "frequency hopping" while she was married to Fritz Mandl, an armament manufacturer who sold munitions to Adolf Hitler. Through a marriage arranged by her parents, Lamarr was Mandl's trophy wife, and she accompanied him to the many business dinners and meetings, where, unbeknownst to the participants, she silently learned about Axis war technology. After four years with Mandl, Lamarr, a staunch anti-Nazi, fled to London, where MGM's Louis B. Mayer "discovered" her and convinced her to move to the U.S.

In Hollywood she met Antheil, who helped her figure out a way to synchronize the frequency hopping between the radio transmitter and receiver. Their invention, which they gave to the U.S. government for free, called for two paper rolls, similar to those used in player pianos, punched with an identical pattern of random holes. One of the rolls would control the transmitter on the submarine while the other would be launched with the receiver on the torpedo. Though ingenious, the device was deemed too cumbersome for use in World War II.

Still, the seminal idea of frequency hopping lingered. By the late 1950s U.S. Navy contractors were able to take advantage of early computer processors for controlling and synchronizing the hopping sequence. Since then, the U.S. military has deployed more sophisticated techniques with ever faster processors in costly, classified devices, including satellite communications systems. And today the technology has become widespread in cell phones and in personal communications services (PCS), among other civilian applications. *—D.R.H.*



HEDY LAMARR, the Hollywood actress, was the co-recipient of a patent (*inset*) for basic technology that is now widely used in cell phones and personal communications services (PCS).

KOBAL COLLECTION; U.S. PATENT OFFICE (*inset*)

necessary, by doing so the devices avoid interference because the transmissions are at such minimal power, with only spurts of data at any one frequency. In fact, the emitted signals are so weak that they might be almost imperceptible above background noise. This feature results in an added benefit of spread spectrum: other radios have great difficulty eavesdropping on the transmission. In practice, only the intended receiver may even know that a transmission is taking place.

The covert nature of spread spectrum was initially its main attraction. During World War II, the U.S. military became interested in an intriguing device that actress Hedy Lamarr had co-patented [*see box above*]. The concept was simple enough—instead of broadcasting information over a single channel, where the enemy might stumble upon the transmission, the device switched channels continually, broadcasting a little bit of information here and a little bit there, in accordance with a secret code known only to the transmitter and the intended receiver. This repeated hopping of frequencies would make it extremely difficult for the enemy to pluck the entire transmission from the surrounding noise. But Lamarr's device was deemed impractical because it relied on an unwieldy mechanical contraption to perform the frequency hopping.

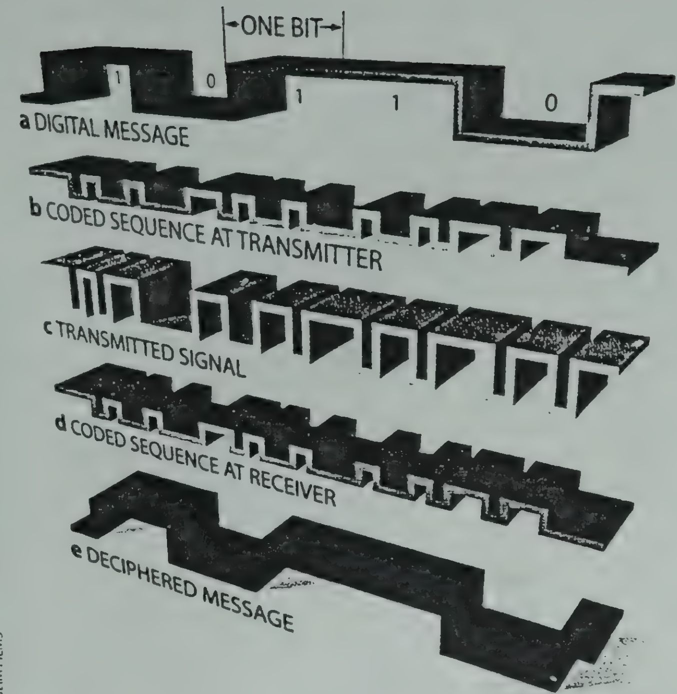
Subsequent advances in electronic circuitry, however, have made spread spectrum feasible. Semiconductor chips, crammed with thousands of transistors, can broadcast digitized packets of data in a seemingly random pattern over many channels. The receiver, designed to hear the signals in accordance with the precise and proprietary sequence of the sending radio, is able to pull the fragmented information in the right order from the different frequencies. In addition, when the receiver encounters missing or corrupted packets, it can signal the transmitting radio to resend those packets. Also, a technique called forward error correction can be used to improve the chances that the data are received correctly the first time.

Electronic technologies have enabled another method of spectrum spreading: direct sequence, in which the transmitted information is mixed with a coded signal that, to an outside listener, sounds like noise. In this alternative to frequency hopping, each bit of data is sent at several different frequencies simultaneously, with both the transmitter and receiver synchronized, of course, to the same coded sequence.

More recently, further advances in chip technology have produced digital signal processors that can crunch data at

high speed, use little power and are relatively inexpensive. The improved hardware allows more sophisticated spread-spectrum techniques, including hybrid ones that leverage the best features of frequency hopping and direct sequence, as well as other ways to code data. The new methods are particularly resistant to jamming, noise and multipath—a frequency-dependent effect in which a signal reflects off buildings, the earth and different atmospheric layers, introducing delays in the transmission that can confuse the receiver.

In 1985 the FCC finally permitted the unlicensed use of spread-spectrum radios by the public, albeit with several restrictions. The radios must operate under FCC regulations in what are called the unlicensed industrial, scientific, medical (ISM) bands. More important, the radios are forbidden to operate at greater than one watt, and the transmissions must be spread a minimum amount across the assigned spectrum.



SLIM FILMS

DIRECT SEQUENCE is another technique for spreading a signal at low power over the radio spectrum. A digital message of "10110" (*a*) is mixed with a coded sequence (*b*). The resulting signal (*c*) is then transmitted so that each bit of the original data is sent at several different frequencies. This redundancy increases the chances that the message will get through even in crowded metropolitan areas, where interference is a problem. The receiver then uses the same coded sequence (*d*) to decipher the transmission and obtain the original digital message (*e*).

These restraints notwithstanding, the 1985 (and later) FCC rules have already spawned the development, manufacture and marketing of a wide range of "no license required" products. Because mass manufacturing has yet to occur, spread-spectrum products for data transmission from the 60 or so current vendors carry premium price tags that have limited the technology mainly to large organizations, such as businesses, schools and libraries. Today a radio that can handle near-Ethernet traffic (10 megabits per second, suitable for high-speed computer communications) up to a distance of about 40 kilometers (25 miles) costs $11,000. Devices with lower capability—operation at T1 speeds (1.5 megabits per second) to a range of 25 kilometers or so—cost $1,500. For very short ranges, such as for communications within a building, wireless local-area network (LAN) cards for personal computers are priced as low as $250.

There is every reason to believe these prices will drop as manufacturing volumes increase to meet the growing market demand for higher bandwidth and secure wireless connections from PCs to the Internet. In the future, people may, for example, routinely rely on wireless transmission to reach a central system that would then connect to a traditional network of ground-based lines. We predict that reliable, secure data radios operating at T1 or higher speeds to a range of more than 30 kilometers will soon cost less than $500 each.

Where is this technology headed? Transmitters and receivers are becoming fully digital. That trend, combined with the rapid development of cell-based wireless systems, will open up a wide range of services based on spread spectrum. The services will rely on intelligent networks containing "smart" transceivers and switches as basic components. Such devices would, for instance, know which of the varied spread-spectrum techniques to use in a given situation to ensure that the information will be transmitted without error. These new networks will increasingly involve a diverse mixture of links and switches, some ground-based, that are owned by different entities.

The Internet today represents the best example of the self-regulating mechanism that will be necessary in the new radio environment. The creation of a similar, decentralized structure for the optimal sharing of the radio spectrum will require a substantial effort by a combination of telecommunications experts and entrepreneurs working with the various regulatory bodies around the world. We believe the deployment and growth of such a system is achievable through increasingly "smart" electronics, and we envision a self-governing set of protocols that are built into these intelligent devices. As advanced radios are deployed, society must tackle the crucial issue of incorporating both positive and negative incentives within the network infrastructure itself to make the best use of a shared common resource—the radio spectrum.

The Authors

DAVID R. HUGHES and DEWAYNE HENDRICKS recently helped to install spread-spectrum radios in Ulaanbaatar to connect eight scientific and educational institutions in that Mongolian city. Hughes is a principal investigator for the National Science Foundation Wireless Field Tests. Hendricks is CEO of Warp Speed Imagineering in Fremont, Calif.

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Commercial Satellite Communication Applications

Course No. 9SV109

Reference 4

The Orbiting Internet
"Fiber in the Sky"

THE ORBITING INTERNET

Fiber IN THE Sky

Broadband satellite systems stand ready to bring multimegabit data rates worldwide. Sounds great. What's the catch?

By John Montgomery

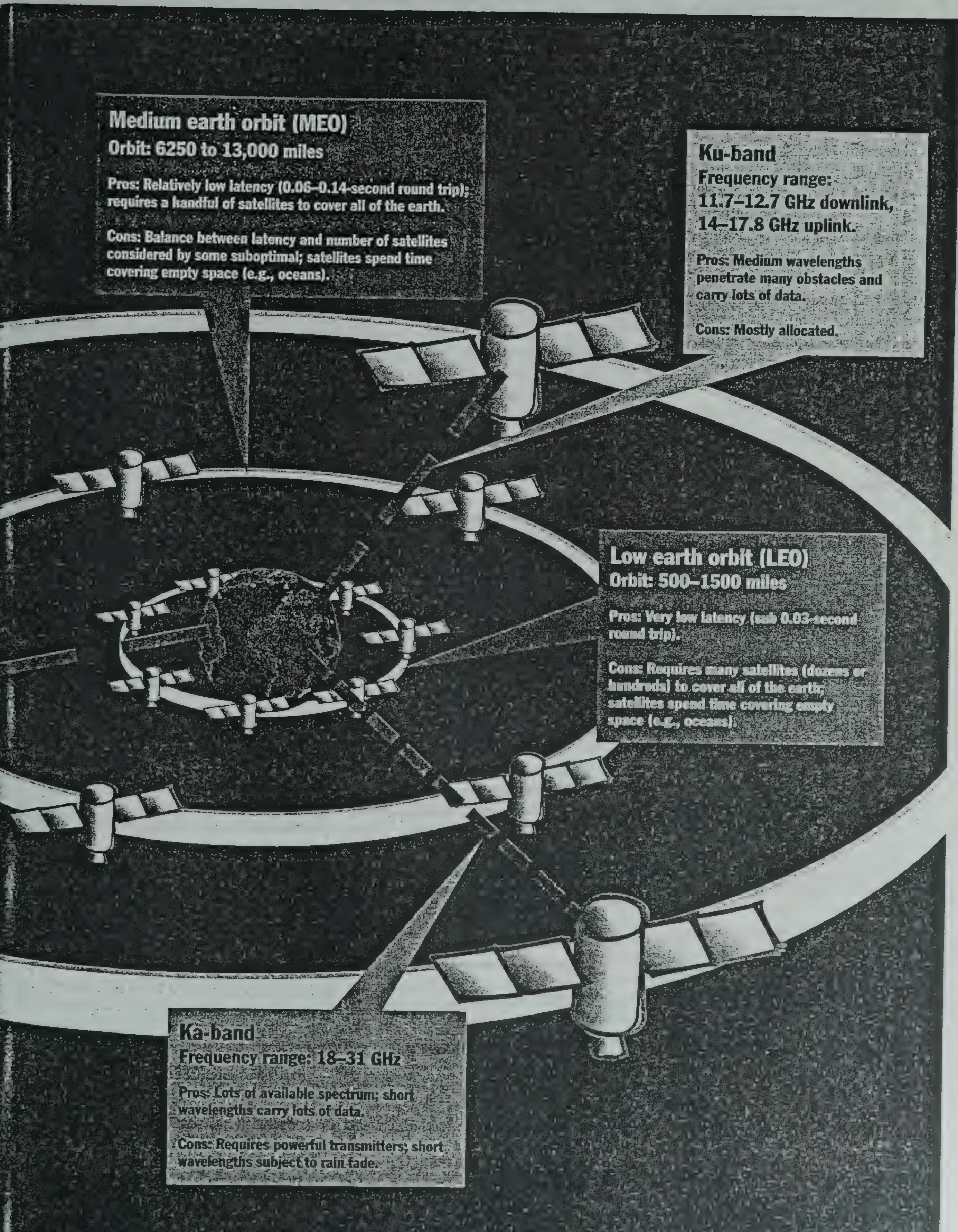
Something special is in the air: your data. Or, at least, it's about to be. The technological and regulatory hurdles to create true high-speed satellite networks have fallen. We've seen low- and mid-bandwidth systems such as Motorola's Iridium and Hughes' DirecPC. But those were almost a parlor trick compared to the promise of 2 Mbps, 20 Mbps, and even 155 Mbps streaming down from the sky. And all you need is a small antenna, a satellite-to-computer gateway (a small black box), and the service itself. In all, you'll probably buy satellite service pretty much the way you buy Internet service from an Internet service provider (ISP) today.

So, it's time to ditch your T1 lines and asynchronous transfer mode (ATM) hardware, right? Not quite yet. Just as Iridium's universal telephone didn't kill the cellular phone, broadband satellite systems won't kill terrestrial lines. Every broadband satellite system creator I talked to was clear that broadband satellite systems will complement terrestrial networks. They will provide high-speed service where terrestrial infrastructure does not exist, and they will enable easy multipoint distribution of video. But high-speed, low-cost landlines are here to stay.

So where *will* these emerging data networks fit in? Better yet, *how* will they fit in? What makes them different from each other? Simple questions, it seems. The answers are also simple—at least until you start to dig. By examining some of the main systems in development, I was able to determine that these systems, while touting much the same capabilities, are vastly different. Some of the most visible ones may prove the most difficult to implement. Some of the most staid-looking

The Air Up There

The two primary considerations with any satellite system are how far from the earth it is (its orbit), which affects latency, and the spectrum it uses, which affects how powerful the signal needs to be and how much data it can carry.



Medium earth orbit (MEO)
Orbit: 6250 to 13,000 miles
Pros: Relatively low latency (0.06–0.14-second round trip); requires a handful of satellites to cover all of the earth.
Cons: Balance between latency and number of satellites considered by some suboptimal; satellites spend time covering empty space (e.g., oceans).
Ku-band
Frequency range: 11.7–12.7 GHz downlink, 14–17.8 GHz uplink.
Pros: Medium wavelengths penetrate many obstacles and carry lots of data.
Cons: Mostly allocated.
Low earth orbit (LEO)
Orbit: 500–1500 miles
Pros: Very low latency (sub 0.03-second round trip).
Cons: Requires many satellites (dozens or hundreds) to cover all of the earth; satellites spend time covering empty space (e.g., oceans).
Ka-band
Frequency range: 18–31 GHz
Pros: Lots of available spectrum; short wavelengths carry lots of data.
Cons: Requires powerful transmitters; short wavelengths subject to rain fade.

systems may beat every other system to the punch.

Playing with the Bands

Satellite communications is nothing new. For years, you could hook up a very small aperture terminal (VSAT) system and buy time on a satellite. Dennis Conti, vice president of VSAT at Hughes Network Systems, says that a VSAT system can deliver up to 24 Mbps in a point-to-multipoint link (e.g., a multicast) and up to 1.5 Mbps in a point-to-point link. Pretty impressive statistics.

But, according to Tony Trujillo, director of corporate communications at Intelsat, a leading global satellite operator, with VSAT, "customers buy very specific time on a specific satellite." This creates a system that's good for predictable communications (e.g., periodic uplinks by news agencies or satellite offices), but not so good for the ad hoc networking that most of us are used to.

For "anytime, anywhere" networking, you need new technologies. Primary among them are more tightly focused beams and digital signal technology, which together can increase frequency reuse (and thereby increase bandwidth) and reduce dish size from meters to centimeters. According to some, you also need a large and unused chunk of the electromagnetic spectrum.

All these technical requirements began to come together in 1993, when NASA launched its Advanced Communication Technology Satellite, or ACTS (see the text box "NASA Gets into the ACTS" on page 61). ACTS pioneered the testing of an all-digital, Ka-band (20–30 GHz), spot-beam, geosynchronous earth orbit (GEO) satellite system—for definitions of these terms, see the text boxes "The Air Up There," "NASA Gets into the ACTS," and "I'm with the Band"—capable of delivering hundreds of megabits per second of bandwidth. With NASA showing that such a system could work (and offering time on the system to interested institutions), it was not long before others were interested. Very interested.

Earlier this year, the FCC granted orbital locations and Ka-band licenses to 13 companies. Some are names you may recognize: EchoStar, Hughes, Loral, and Motorola. Others may be more obscure: Ka-Star, NetSat 28, PanAmSat, and Teledesic. Regardless of name recognition, they all aim to bring information into your home and office at incredible speeds—up to 155 Mbps. These broadband systems are not going on-line before 2000 (although Loral's Cyberstar will start offering 400-Kbps rates next year), and most will not be fully operational until 2002.

What are they going to use it for? According to the FCC, just about everything you would use a terrestrial line for: desktop-to-desktop videoconferencing, Internet access, electronic messaging, faxing, telemedicine, direct-to-home video, electronic transaction processing, distance learning, and even news gathering.

Is This Trip Necessary?

Who needs this stuff, anyway? Most of the market that needs data services seems to be well served by landlines. "These systems will be important globally. In the U.S.? We're well served, although things are changing quickly," says Erwin Edelman of NASA's Lewis Research Center.

A first guess at an obvious market is in places that have underdeveloped communications infrastructures. In some countries, stringing copper or fiber is out of the question—the empty distances to cover are too great and available money is too little. (There are places where people will rip down any copper wire to resell it.) Still, a wireless, solar-powered telephone has some appeal. Of course, you don't need a broadband satellite to make phone calls, though. Systems such as Iridium will likely serve that market. Marco Caceres, of the Teal Group, says, "For most of the people in the world, the services Ka-band supplies aren't interesting."

So who *does* need this new class of broadband satellite communications? The first answer I heard from virtually every broadband vendor is the same: multinational corporations. "For some applications, landlines will always be superior. But when your reach is diverse and you have last- and first-mile problems, then satellite will be the better choice," says Edward Fitzpatrick, Hughes Communications'

Physics Is Everything

When it comes to communications satellites, what chunk of the radio spectrum they can use determines virtually everything—what they can do, how powerful they'll be, and how much they're going to cost. Why? Physics.

Let's start with the basics. You'll hear the terms frequency and wavelength bantered about quite a bit, so you have to know what they are. Remember that radio comes in waves; imagine a sine wave for simplicity's sake. How often a crest of a radio wave passes a point during a given time is called its frequency. Frequency is measured in hertz (Hz)—cycles per second—and its variations: kilohertz (kHz), megahertz (MHz), gigahertz (GHz), and so on. The distance between crests is the wavelength, and it is usually measured in some multiple or fraction of meters.

Radio frequency and wavelength are related—higher frequencies mean shorter wavelengths and vice versa. Why? If you know how many pulses are hitting you in a second and how far apart the crests are, you know the speed, right? Well, the speed is constant: Radio waves travel at the speed of light (i.e., 300,000 kilometers per second, or 187,500 miles per second, which is usually rounded to 186,000 miles per second). Therefore, if wavelength goes up, frequency has to go down and vice versa.

Different wavelengths have different properties. Long wavelengths can easily travel long distances and go through obstacles. Think of AM radio. At around 1 MHz, its waves are about 300 meters long. You can pick up AM stations much farther away than FM stations, which are up around 100 MHz, or 3 meters. These longer waves can pass through or around buildings and mountains. The shorter the wavelength (i.e., the higher the frequency), the more easily the waves can be stopped. When frequencies get high enough (up in the tens of gigahertz), small things such as leaves and even rain can stop them—a problem called "rain fade." It takes a lot of power to get around rain fade. More power means bigger transmitters or more focused antennas, which usually means satellites that are more expensive.

The flip side of this is that higher frequencies (i.e.,Ka- and Ku-bands) enable transmitters to transmit more information per second. That's because information is typically encoded at a certain part of the wave—the crest, valley, beginning, or end. (In the film *Crimson Tide*, Denzel Washington's character wanted to verify a signal using the extremely low frequency [ELF] antenna. Unfortunately, ELF transmission was so slow that they couldn't get a complete message before they had to start evading the bad guys.) The trade-off is that higher frequencies mean more information per second, but they require higher power to avoid getting blocked, larger antennas, and more expensive equipment.

Broadband Satellites, Broadly

	Cyberstar	Celestri	Astrolink	Teledesic	Spaceway	Skybridge
Backers	Loral	Motorola	Lockheed	Bill Gates, Craig McCaw, Boeing	GM-Hughes	Alcatel with Loral
Use	Data, video	Voice, data, video-conferencing	Data, video, rural telephony	Voice, data, video-conferencing	Data, multimedia	Voice, data, videoconferencing
Altitude (miles)	22,300	875 and 22,300	22,300	435	22,300	911
Spectrum	Ku (initial) and Ka	Ka and also 40–50 GHz	Ka	Ka	Ka	Ku
Antenna size (est.)	16 inches (initial Ku)	24 inches	33–47 inches	10 inches	As small as 26 inches	TBD
Data throughput	400 Kbps (initial Ku); up to 30 Mbps (Ka)	Up to 155 Mbps transmit and receive	Up to 9.6 Mbps	16 Kbps–64 Mbps (up to 2.048 Mbps on symmetrical links)	Up to 6 Mbps	16 Kbps–2 Mbps to satellite; 16 Kbps–60 Mbps to user; any multiple of this for business users
User terminal cost (est.)	$800 (initial Ku); $1000 (Ka)	Starts at $750	Under $1000 to $2500	N/A	Under $1000	$500 (consumer)
System cost (billions)	$1.05	$13	$4	$9	$3.5	$3.5
Operation starts	1998	2002	Late 2000	2002	2000	2001
Number of satellites	TBD for Ku; 3 likely for Ka	63 LEOs, 9 GEOs	9	288	8 initially	64
Access method	FDMA, TDMA	FDMA, TDMA	FDMA, TDMA	MF-TDMA, ATDM	FDMA, TDMA	CDMA, TDMA, FDMA, WDMA
Intersatellite communication	Undecided	Yes	Yes	Yes	Yes	No

NASA Gets into the ACTS

The whole Ka-band craze can be traced to NASA. When it launched its Advanced Communication Technology Satellite (ACTS) in September 1993, it began a research-and-testing project to determine what it needed to do to make Ka-band satellite communication work. "All the current Ka-band filings [to the ITU] are a direct tribute to ACTS technology," says Erwin Edelman, demonstrations coordinator at NASA's Lewis Research Center.

ACTS proved that it was possible to create an all-digital Ka-band system that could overcome rain fade, a signal-degradation problem resulting from short wavelengths passing through rain. ACTS is a TDMA-based system that uses many of the things you'll find in commercial Ka-band satellite systems, including spot-beam (or multibeam) technology, on-board storage and processing, and all-digital transmission.

Spot-beam. This technology enables an antenna system to subdivide a single large footprint (area of coverage) into many subfootprints. It can then focus these subfootprints (or spot beams) on particular areas. Subdivision enables a high degree of frequency reuse. Rather than spreading the entire frequency over the entire footprint, it spreads subsets of the frequency over smaller footprints. And, most important, it reuses these subsets in nonadjacent footprints.

On-board storage and processing. Most satellites are "bent pipes"—a signal goes up and then goes back down immediately. On-board storage and processing enables the caching of information until a spot beam is aimed; it also enables intersatellite switching.

All-digital transmission. To overcome rain fade, signals need to be digital so that they can incorporate error codes. According to Edelman, ACTS uses the same TDMA system that you'll find in terrestrial cellular systems.

Together, these technologies enable nearly unheard-of data rates. "The ACTS is theoretically capable of communicating over three 622-Mbps channels," says Edelman. In case you're wondering, that's about 400 T1 lines.

vice president for Spaceway.

Of course, there are even places in the U.S. that won't get broadband data service for a long time. For example, until recently, BYTE's office in Peterborough, New Hampshire, would have had serious problems getting anything more than a T1. But imagine if one of these satellite services had been in place—we could have tapped it no matter where we were. That is the second market that most of the broadband vendors cited—low-population areas.

The main problem satellite systems solve is getting high-bandwidth access to places without a high-bandwidth infrastructure. It's unlikely that a satellite system could compete with Digital Subscriber Line (DSL) to the home or fiber to the office—if you can get those services. Still, if you're in a rural area of the U.S.—or in a low-population area in any country—you may not be able to get such services. Satellites will deliver them, enabling not only high-speed Internet browsing (a technology that some industry pundits focus on relentlessly), but all forms of high-speed networking, including such things

as videoconferencing, collaborative work sharing, and telemedicine.

Is the telephone dead? Says Teledesic president Russell Daggatt, "It's not going to replace the current phone network—the capacity isn't there." Put simply, terrestrial networks and satellite networks will complement each other. "Nobody's going to put up a satellite dish and take out their telephone," agrees Ron Maehl, president of Cyberstar. "We don't believe satellite should compete with fiber or Asymmetric Digital Subscriber Line (ADSL)—it should complement them, especially for bursty service. Use the technologies for what they're best suited."

LEO vs. GEO

But bandwidth is only half the story. The other half is latency—the amount of time for your data to get from point A to point B. Here is where the rubber starts to meet the road. It's all well and good to talk about high-bandwidth satellite systems—that technology has existed in VSATs for years. But to deliver on the promise of highly interactive satellite networks is a different matter altogether. "There are some applications not suitable to satellite," says Karl Savatiel, president of Astrolink and vice president for broadband systems at Lockheed. "Bond transactions, for example, are too latency-sensitive."

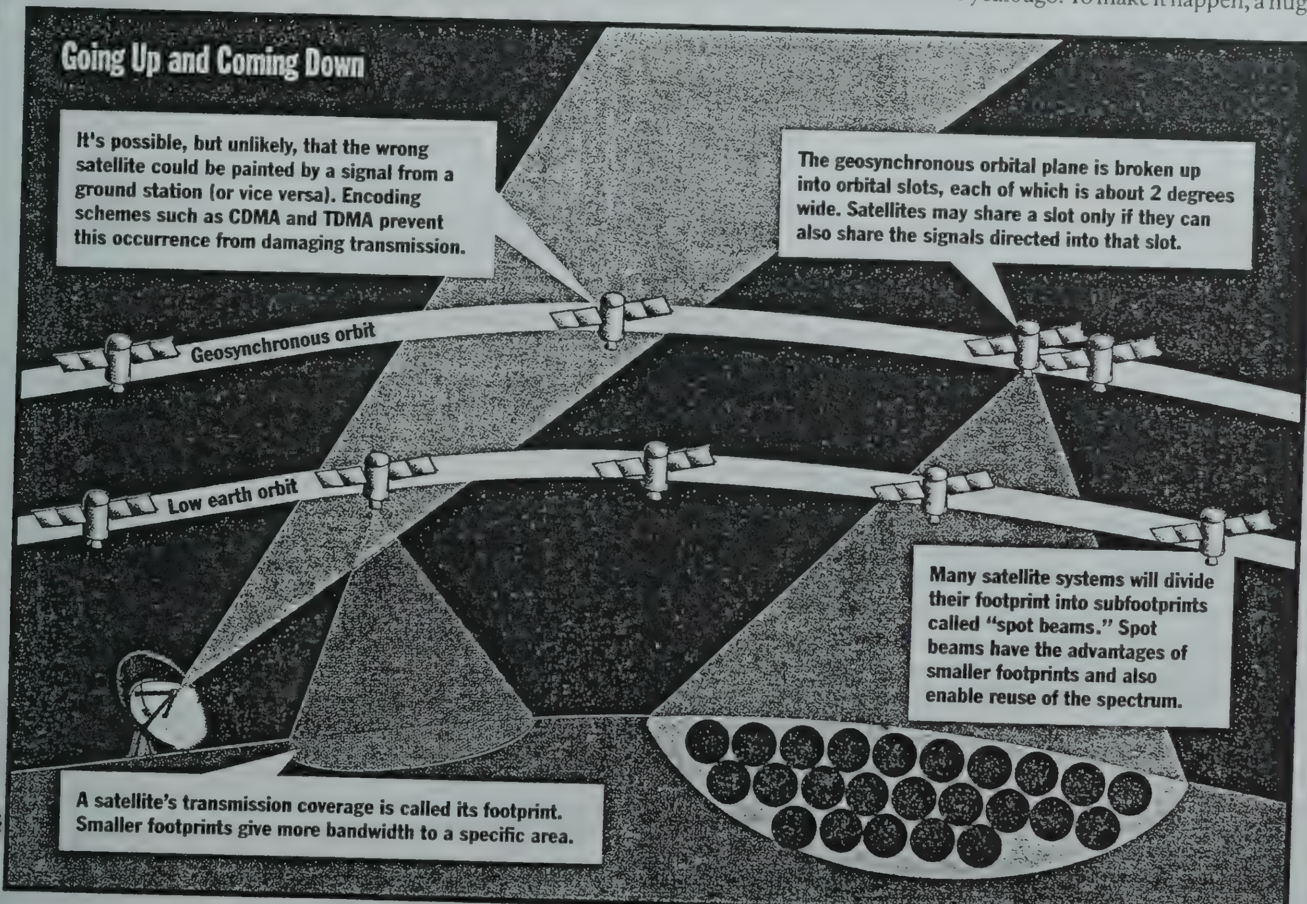
That is true—at least for a GEO system such as Astrolink. GEO satellites park some 22,300 miles above the equator: 0.24 second—an eon to computers—of round trip away. With that kind of latency built into the system (not counting whatever latency is added by the various gateways and translations the data must go through), a telephone conversation is an annoying, awkward mess. And any kind of interactive application has to be nonlatency-sensitive. So Bank of America can probably forget putting its on-line transaction processing (OLTP) system through a geostationary satellite. Such systems include not only Astrolink, but Loral's Cyberstar and Hughes' Spaceway projects.

So here's a simple solution: Move the satellites closer to earth. That's just what systems such as Teledesic, Alcatel's Skybridge, and Motorola's Celestri will do. With low earth orbits (LEOs) under 1000 miles, these systems offer latency that's barely apparent: hundredths of a second.

Of course, it's not that simple. While GEOs are a well-known technology (TV broadcasts, for example, have been using them for decades), LEOs are new and face new challenges. Perhaps the biggest one is that you need a lot of them to get total global coverage. At one point, Teledesic planned a constellation of more than 800 satellites, for example (that number recently dropped to 288 when it signed an agreement to work with Boeing). Until recently, the concept of launching dozens or hundreds of multimillion-dollar satellites was a pipe dream.

Each of Teledesic's 288 satellites will cost in the realm of $20 million, according to Daggatt. That's $5.76 billion just in satellites. That does not include launch fees or insurance—which, in the case of some satellite systems, is the price of the satellite again.

Price is only one issue. Who is going to launch all these satellites? Teledesic has set an 18-month to two-year launch window to get its 288 satellites airborne. All told, the LEO system creators are talking about putting more satellites into orbit in the next five years than the world has put into orbit since the Soviets launched Sputnik 40 years ago. To make it happen, a huge



Some Satellite Personal Communications Systems

	Ellipso	Odyssey	ICO	GlobalStar	OrbComm	Iridium
Backers	Westinghouse, Harris, Israeli Aircraft Industries	TRW, TeleGlobe	Inmarsat, Hughes Space Telecom	Loral, Qualcomm, Alcatel, France, and many others	Orbital Sciences, Teleglobe, and many others	Motorola, Raytheon
Use	Voice, fax, messaging	Voice, fax, messaging	Voice and messaging	Voice, data, and fax	Messaging and tracking	Voice, paging, data, fax
Altitude (miles)	Elliptical: 325–4904; 5025	6471	6459	884	484	483
Spectrum request	UHF	L, S, and Ka	S and C	L, S, and C	VHF	L and Ka
Data throughput	0.3–9.6 Kbps	9.6 Kbps	2.4 Kbps	7.2 Kbps	56.7 Kbps	2.4 Kbps
User terminal cost (est.)	$1000	$300	Several hundred	$750	Starting at $500	$2500–$3000
System cost (billions)	$0.75	$1.8	$2.6	$2	$0.33	$3.7
Operations start	1998	2000	2000	1998	1995	1998
Number of satellites	17	15	12	56	36	72

jump in launch capacity is necessary.

Once the LEO satellites are in orbit, there's an entirely new set of problems. First, there's the matter of space junk: leftovers from past space missions of all sizes, speeds, and lethality. "With all these satellites in orbit, it's possible that debris will start running into them," says the Teal Group's Caceres. "They aren't that far from manned systems." Great—just what Mir needs.

More Problems for LEO

If the satellites don't get aced by space junk, they still will fall into the atmosphere eventually. Unlike GEOs that, when their operational life is over, move into a parking orbit a few miles higher than normal, LEO systems will burn up in the atmosphere, like SkyLab. Although satellite life may be 10 or 12 years, "with LEOs, you must have a plan for satellite replacement," says Myron Wagner, vice president and director of engineering for Motorola's Celestri system (a hybrid LEO/GEO system). It's possible, however, and Wagner cites Iridium as a pioneer in this field.

Let's say you solve these challenges. There are more. For example, there's the matter of acquiring and tracking these fast-moving satellites. A LEO satellite may be visible for only 20–30 minutes before it passes over the horizon. This poses no small feat for aiming the antenna and keeping the link active.

A technology called a phased-array antenna solves the antenna problem. Unlike a satellite dish, which mechanically tracks satellite locations, phased-array antennas are self-aiming boxes consisting of many smaller antennas. They can track several satellites using the slightly different signals received by the array of antennas—without physically moving, reducing wear and tear among other advantages.

The problem of keeping a link active when your satellite disappears every half hour is solved by keeping at least two satellites in view at all times (many LEOs will keep three or more in view). The antenna array is aware of all the satellites' positions and starts a new link before it severs the one to the setting satellite. This is "make before break" in satellite parlance.

All LEOs have to solve these challenges. Some of them have others, too. For example, there is the matter of whether a LEO constellation uses intersatellite routing. The problem is, how do you get a signal from the footprint of one satellite into the footprint of another? In other words, if a LEO user in New York wants to communicate with one in Moscow, the LEO system needs to figure out how to route the signal.

If the system is a bent pipe, such as Alcatel's Skybridge, the satellites don't have to be very smart. The LEO satellite over New York will beam the signal down to a ground station, which will route the signal over landlines to a ground station near Moscow. That station will feed the signal up to the LEO satellite over Moscow, which will in turn bounce it down to the user there.

According to Motorola's Wagner, however, "Bent pipes are not good. There are too many hops from sky to earth." And that means dreaded latency—defeating the whole reason LEOs are supposed to be better than GEOs. Instead, some systems, including Teledesic and Celestri, use satellite-to-satellite routing. The Teledesic constellation communicates in the 40–50-GHz band. Celestri uses lasers for its links.

The downside is, of course, that each satellite has to have more communications and tracking hardware—more intelligence—and therefore a higher price than a bent-pipe system. Also, the performance gain over a bent pipe is not tremendous—a few hundredths of a second.

Alcatel's Skybridge faces yet another set of challenges, because it selected the Ku-band instead of the Ka-band. According to Mark MacGann, director of public affairs for Skybridge, this lower frequency lets Skybridge be "the cheapest system in low earth orbit." That's because Skybridge can use less powerful transmitters. The Ku-band is pretty crowded, though, with many GEOs working there, and that spells interference when Skybridge satellites are over the equator. "We took the GEO arc," says MacGann, "and defined a nonoperating zone of a minimum of plus or minus 10 degrees. Once a Skybridge satellite comes

within that arc, it shuts off its offending beams, and the ground terminal switches to another satellite." A simple solution.

Niches in the GEO Sphere

In spite of the concerns of latency, GEOs and LEOs will likely coexist. Guy Christensen, of Leslie Taylor and Associates, sums up the markets based on whether the system is a GEO, with its inherent 0.24-second delay, or a low-latency LEO. LEOs will be good for high-speed networking, teleconferencing, and telemedicine—interactive applications. GEOs will be better for information downloading and video distribution—broadcasting and multicasting.

Some GEO vendors disagree. Hughes' Conti says, "Today, we're able to use GEO satellites to transport at least 24 Mbps of broadcast IP data and over 2 Mbps of point-to-point TCP/IP data. The latter uses technologies such as TCP spoofing. HNS has been using this technique for over three years to deliver Internet/intranet content at high speed to both consumers and enterprises." If necessary, ground terminals using the Spaceway system will use similar TCP spoofing technologies.

But there's still the 0.24-second delay that you just can't get around. Daggatt says that any lossless protocol is going to have problems with this latency. Even if TCP spoofing works (and he is skeptical about that, given TCP's 64-Kb buffer), there's the matter of other protocols. "It's reasonable to think that future network protocols will be designed for terrestrial networks," he says. "You need systems that offer low error rates and low delay. People talk about voice and data as though there were two types of data. They aren't. And if the network doesn't work for voice, it won't work for other applications."

The Air Up There

One easy way to distinguish among the many new satellite systems is by how high up they are. This is also one key factor in determining how many satellites a system needs for worldwide coverage and how powerful those satellites must be. If an antenna can cover 15 degrees, for example, that same arc covers a much smaller area if the satellite is 200 miles away than if it's 20,000 miles away. However, it will require much less power to deliver a signal from 200 miles away than from 20,000 miles away. Satellite people have four basic terms to describe different altitudes.

GEO: Short for geosynchronous earth orbit, GEO satellites orbit at 22,238 miles above the earth's equator. At this altitude, the period of rotation of the satellite around the earth is exactly 24 hours. The satellite seems to stay above exactly the same point on the earth's surface. (As a footnote, this orbit is called a Clarke orbit, named for the author Arthur C. Clarke, who first posited in 1945 that it should be possible. According to BYTE senior contributing editor Jerry Pournelle, Clarke never got the patent he sought for figuring it out.) Most of today's satellites are GEOs, as are planned broadband systems such as Hughes' Spaceway and Loral's Cyberstar.

GEOs require few satellites to cover the entire earth's surface. However, they're saddled with a 0.24-second latency for a signal to travel from earth to satellite and back to earth again. GEOs also need to obtain specific orbital slots around the equator to keep far enough apart, each separated by 2 degrees, or about 1000 miles, according to Erwin Edelman, demonstrations coordinator at NASA's Lewis Research Center. The ITU and, in the U.S., the FCC mete out these slots.

MEO: According to Marco Caceres of the Teal Group, medium earth orbit satellites orbit at altitudes between 6250 and 12,500 miles. Unlike GEOs, their position changes relative to the earth's surface. At their lower altitudes, you need more of them to achieve complete coverage of the earth's surface, but the latency reduces substantially. Right now, according to Caceres, there aren't many MEOs, and the ones in orbit are used for positioning.

LEO: Low earth orbits promise extremely high bandwidth and low latency. Plans exist for huge constellations of hundreds of satellites that will cover the entire globe. LEOs generally orbit below 3125 miles. Most of them are much lower: only 400–1000 miles. At these altitudes, latency reduces to nearly negligible times–hundredths of a second.

Three kinds of LEOs handle different amounts of bandwidth. Little LEOs are low-bandwidth applications (tens to hundreds of Kbps) such as paging and include systems such as OrbComm. Big LEOs can handle paging, cellular services, and some data transmission (hundreds to thousands of Kbps). Examples include GlobalStar and Iridium. Broadband LEOs (sometimes called mega-LEOs) operate in the Mbps range and include Teledesic, Celestri, and Skybridge.

HALE: High-altitude, long-endurance platforms are basically a solar-powered, lightweight airplane or lighter-than-air craft that hover over an unmoving spot some 70,000 feet above the earth's surface. Not often talked about, and right now primarily a research venture. An example of a HALE that uses blimps is Skystation.

LEO Meets GEO

One of the systems I looked at is considering offering the best of both worlds: a hybrid solution. Motorola's Celestri plans a LEO constellation of 63 satellites (initially) coupled with one GEO satellite over the U.S. Motorola has the rights to eight more GEO orbital slots if it needs them. The LEO constellation and the GEO satellites will be able to communicate directly through a satellite-to-satellite network.

"We want users to be unaware of the kind of system they're using. The only way we know to do that is with a LEO configuration," says Wagner. The hybrid configuration will enable Celestri to take advantage of LEO's shorter delays for interactive uses and GEO's power in the broadcast arena.

Alcatel and Lockheed have had similar thoughts. They are looking at a partnership that will enable Skybridge and Cyberstar to work together through land-based gateways. It's not going to be quite as transparent as Celestri's system, because it will need to route traffic through terrestrial gateways, but it does hint at the power of a hybrid configuration.

Space Security Unit

Once you get beyond the latency and bandwidth issues (which is what the satellite creators spend a lot of time arguing over), there is another challenge: security. If your data is being packaged up and broadcast into space, can't anybody with a scanner just tune in? In theory, the answer is yes. But the access technologies that these systems use—combinations of code division multiple access (CDMA), time division multiple access (TDMA), frequency division multiple access (FDMA), and a bunch of other *x*DMA protocols—make that at least as difficult as it will be to intercept a digital cellular signal. On top of that, many of the networks will offer some kind of internal security systems. But exactly what kind? Well, that gets a bit murky.

All the vendors I spoke with told me that they were aware of the potential security

concerns that customers would have. Few, however, had concrete solutions. Sig Dekany of Astrolink, for example, says, "I can say only that it does involve encryption. Additionally, second-tier security at the user level will come by way of public-key encryption." Representatives at Spaceway and Cyberstar were even less forthcoming, saying only that they were working on the problem and had not yet decided on a solution. Teledesic said that there is encryption within its network, and, if users want, they can add more. That seems to be the general consensus: If you want security, you're going to have to add it yourself.

But is that so different from running private business over any public network? Would you, for example, engage in trusted transactions over the Internet? Of course not. You would purchase some kind of encryption software, a virtual private network (VPN) system, for example. And because all the satellite systems claim that they will be completely transparent to your network, it's likely that the VPN system you purchase for the Internet will work just as well—and just as transparently—over a satellite system.

What the Band Names Mean

Band Name	Frequency Range
HF-band	1.8–30 MHz
VHF-band	50–146 MHz
P-band	0.230–1.000 GHz
UHF-band	0.430–1.300 GHz
L-band	1.530–2.700 GHz
FCC's digital radio	2.310–2.360 GHz
S-band	2.700–3.500 GHz
C-band	Downlink: 3.700–4.200 GHz Uplink: 5.925–6.425 GHz
X-band	Downlink: 7.250–7.745 GHz Uplink: 7.900–8.395 GHz
Ku-band (Europe)	Downlink: FSS: 10.700–11.700 GHz DBS: 11.700–12.500 GHz Telecom: 12.500–12.750 GHz Uplink: FSS and Telecom: 14.000–14.800 GHz; DBS: 17.300–18.100 GHz
Ku-band (America)	Downlink: FSS: 11.700–12.200 GHz DBS: 12.200–12.700 GHz Uplink: FSS: 14.000–14.500 GHz DBS: 17.300–17.800 GHz
Ka-band	Roughly 18–31 GHz

Down-to-Earth Price Tags

What will be the price for this magical universal service? Surprisingly, on a per-bit basis, every company I talked to said it will be probably not much more than what you're paying for your landline services. That may seem like a pretty amazing statement, considering the investment required to get some of these systems running—Teledesic, for example, is forecasting a $9 billion start-up charge (which some critics say is low); Motorola's Celestri is at $13 billion. But Teledesic president Daggatt thinks it's reasonable. "It's a very high-capacity system. And unlike a wire-line network, where all the capacity of the infrastructure is rigidly dedicated to locations and users regardless of whether they are actually using it at any particular moment, Teledesic offers 'bandwidth on demand,' where the system capacity used is limited to that required by a particular user and a particular application at a particular

I'm with the Band

The electromagnetic spectrum is an ongoing problem for everybody. To start off with, the common names for certain frequency ranges—or bands—date back to World War II. But worse, inconsistencies and anachronisms in the regulatory process may make it more difficult than necessary to get the bandwidth that a new system needs.

According to Ed Elizondo, systems engineering consultant at Lockheed, the IEEE has been pushing for a standard naming convention that would be easier to understand. Still, most people refer to segments of the radio spectrum by letter-band classifications that are often vague. In World War II, U.S. and British radar developers named parts of the spectrum with letters, such as L-band, C-band, Ku-band, and Ka-band (see the table "What the Band Names Mean"). The letters were chosen at random, so that the enemy wouldn't know what they were talking about. Over the years, some discrepancies crept into the labels, making some of the designations imprecise.

Many of the satellite system vendors cited the regulatory process as a problem. Skybridge's Mark MacGann puts it this way, "Spectrum is a scarce resource. The ITU has always allocated frequency on a first-come, first-served basis. But that cannot continue."

Indeed, the whole regulatory process could drive a neophyte nuts. According to Lockheed's Karl Savatiel, the process in the U.S. is highly iterative. You file with the FCC for authority to construct radio beacons at a particular frequency (and a position in the case of GEOs). If someone asks for the same frequency, the FCC makes its decision based on the greater public good. If there's a conflict, there may be an auction (which is what happened with the Ka-band when it opened up).

Then the FCC takes all the U.S. filers to the ITU—the international coordinating body. However, because the ITU allocates bandwidth on a first-come, first-served basis, while the FCC is resolving U.S. conflicts, other countries that can resolve conflicts quicker may be getting orbital slots and frequencies that U.S. companies were counting on.

Then it goes back to the FCC's drawing board. "The FCC has teeth in its process," says Savatiel. "If you don't deliver in five years, you lose your slot; the ITU has fewer teeth—you won't lose it for at least nine years."

Until recently, this arrangement hasn't been a problem. However, if future spectrum allocations are as heated as the Ka-band's, the ITU may need to reconsider its process to add more teeth—perhaps a "greater public good" system.

Satellite System Overview

System type	Frequency bands	Applications	Terminal type/size	Examples
Fixed satellite service	C and Ku	Video delivery, VSAT, news gathering, telephony	1-meter and larger fixed earth station	Hughes Galaxy, GE American, Loral Skynet, Intelsat
Direct broadcast satellite	Ku	Direct-to-home video/audio	0.3–0.6-meter fixed earth station	DirecTV, Echostar, USSB, Astra
Mobile satellite (GEO)	L and S	Voice and low-speed data to mobile terminals	Laptop computer/ antenna-mounted but mobile	Inmarsat, AMSC/TMI, ACES
Big LEO	L and S	Cellular telephony, data, paging	Cellular phone and pagers; fixed phone booth	Iridium, GlobalStar, ICO
Little LEO	P and below	Position location, tracking, messaging	"As small as a packet of cigarettes" and omnidirectional	OrbComm, E-SAT
Broadband GEO	Ka and Ku	Internet access, voice, video, data	20-cm, fixed	Hughes Spaceway, Loral Cyberstar, Lockheed Astrolink
Broadband LEO	Ka and Ku	Internet access, voice, video, data, videoconferencing	Dual 20-cm tracking antennas, fixed	Teledesic, Skybridge, Celestri, Cyberstar

Source: Leslie Taylor and Associates

moment. That allows the high system capacity of the Teledesic network to extend to a very large user base."

Other system operators agree. Savatiel says, "The price can compete with underutilized T1s, like 25 percent utilized T1s." Astrolink will be in the range of 20 to 25 cents per minute for 64 Kbps, but remember that you will pay only for time that you use. "If you provide a good value to end users, you'll be rewarded," says Savatiel. Astrolink will word reseller agreements to try to avoid price gouging—a practice more common in countries where telecommunications is a monopoly. Cyberstar's Maehl puts it a different way: "We're trying to wait to see what the market wants." He sees Cyberstar's service coming in at about $20 per month for basic service on its Ku-band system (which has a lower bandwidth than the planned Ka-band system) and a similar price on its eventual Ka-band system.

The price you see as a customer, however, is likely to be set by your service provider. Satellite system creators are wholesale service providers. None of the satellite systems will be selling bandwidth to end users. They'll sell to gateway providers such as telephone companies, who will probably resell the satellite bandwidth to service providers (like ISPs), who will sell to customers.

The goal is to make the satellite systems transparent to end users—you buy the service, and somebody else worries about the plumbing. This transparency is incredibly important. Cyberstar, for example, is working on deals with router vendors to facilitate intelligent routing of hybrid networks. "Satellite guys can't just do satellites—we have to know about the network architecture as well," says Maehl.

Shooting for the Stars

According to analysts conducting research for Motorola, the total telecommunications market is about $650 billion, and that's going to double in 10 years, chiefly due to data communications. In other words, there are a whole lot of people out there needing a whole lot of bandwidth. And we'll need every hose we have to put out that fire: fiber, ATM, Synchronous Optical Network (SONET), *x*DSL, Gigabit Ethernet, cable modems, satellites, and probably a few that haven't even been thought of yet.

"I don't think the fact that it's a satellite system is going to make a difference," says Guy Christensen. He sees all telecommunications systems competing on their availability, price, and speed. That means there are going to be two big winners: whoever gets its broadband service to consumers first, and whoever can offer the most bandwidth with at least not-unreasonable latency.

At this point, the race could fall to any of the companies putting together a broadband satellite system. Or even to someone we've never heard of. The profile of the broadband satellite race has changed a great deal since last spring. AT&T has dropped out. Teledesic changed its configuration. And Motorola is collapsing two of its systems (M-Star and Millennium) into Celestri.

Gentleman, to your launch pads. ■

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Alcatel
Paris, France
+33 1 4058 5858
http://www.alcatel.com/our_bus/telecom/products/space/whatsnew.htm

Hughes Communications, Inc.
Long Beach, CA
310-525-5000
http://www.spaceway.com

Lockheed
Sunnyvale, CA
888-278-7565
408-543-3103
http://www.astrolink.com

Loral
Palo Alto, CA
650-852-5736
http://www.cyberstar.com

Motorola
Chandler, AZ
602-732-4018
http://www.mot.com/

Teledesic
Kirkland, WA
425-602-0000
http://www.teledesic.com

Commercial Satellite Communication Applications

Course No. 9SV109

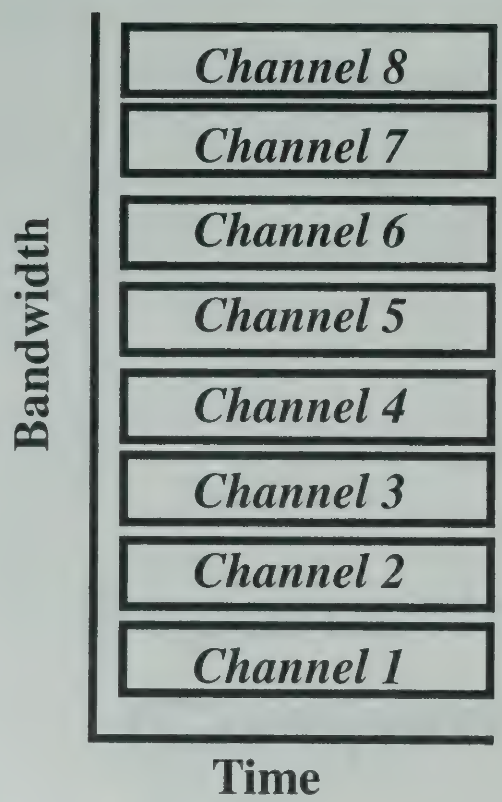
Reference 5a

Engineering Issues & Design Choices (Comparison - TDMA, FDMA)

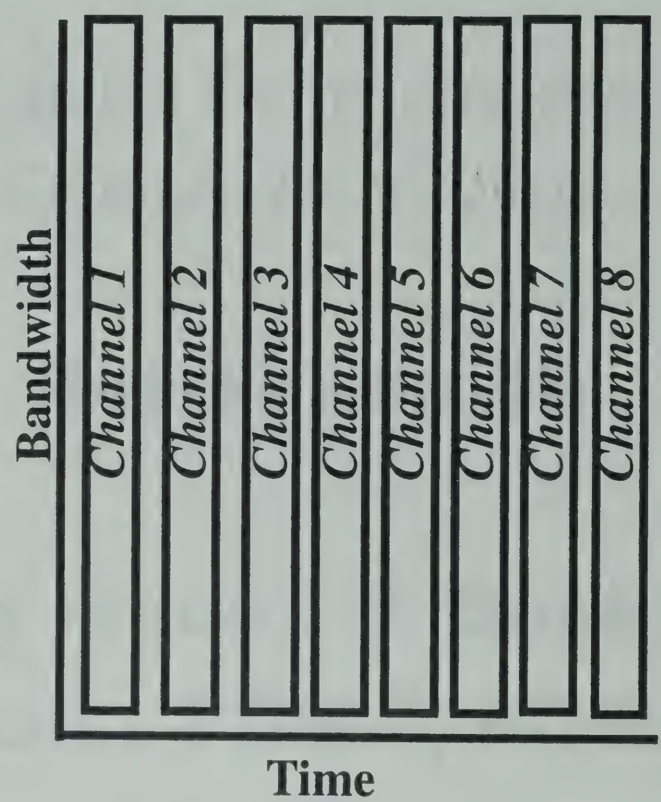
Engineering Issues and Design Choices

Comparison

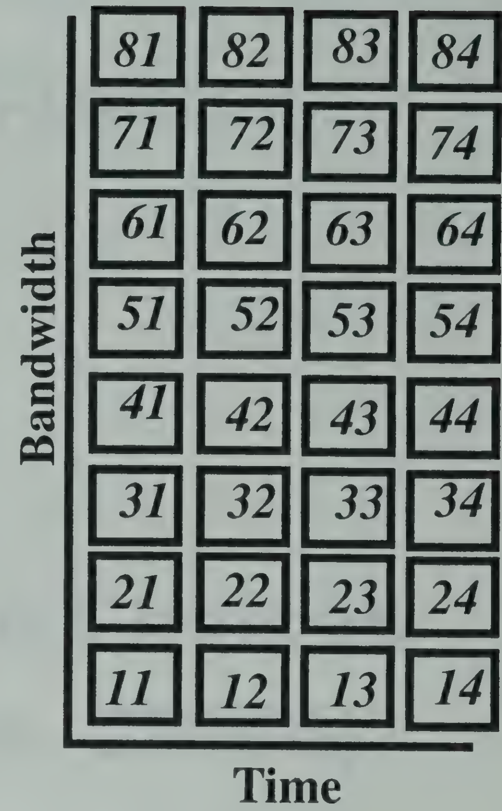
TDMA and FDMA



Frequency Division Multiplexing (FDM)



Time Division Multiplexing (TDM)



Combined TDM/FDM

Commercial Satellite Communication Applications

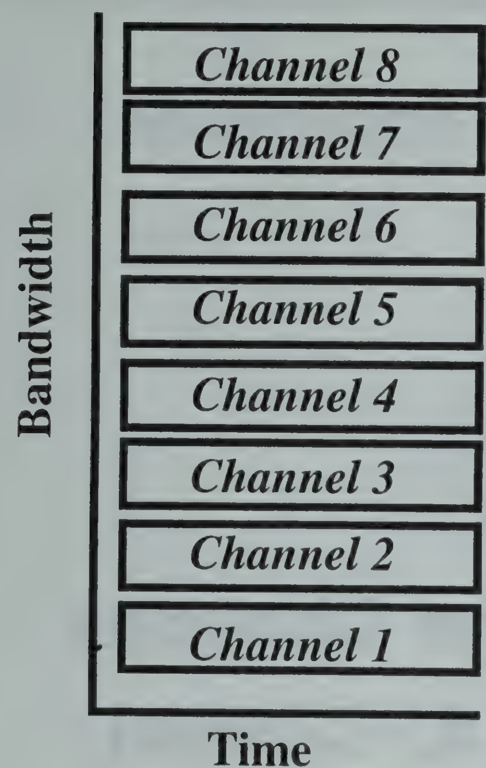
Course No. 9SV109

Reference 5b

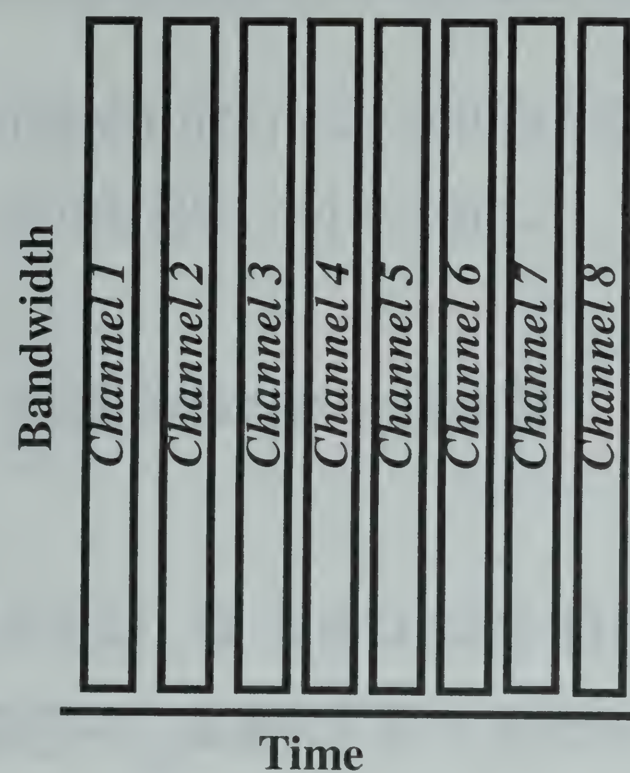
Engineering Issues & Design Choices (Comparison - TDMA, FDMA, CDMA)

Engineering Issues and Design Choices

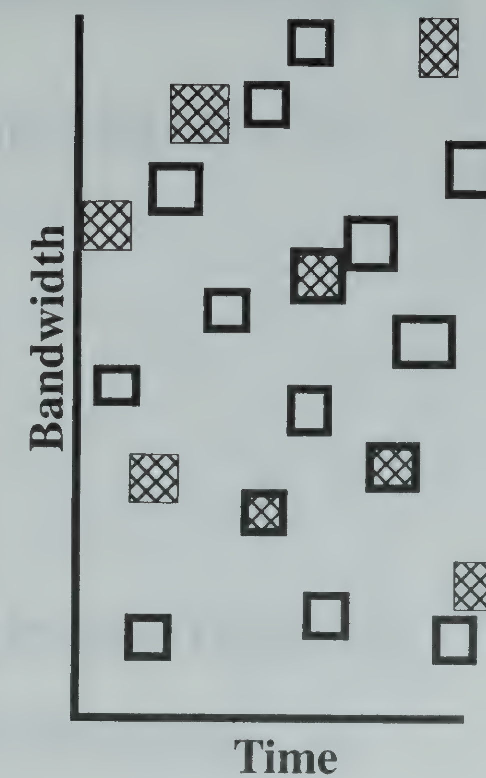
Comparison
TDMA, FDMA , CDMA



Frequency Division Multiplexing (FDM)



Time Division Multiplexing (TDM)



Code Division Multiple Access

Commercial Satellite Communication Applications

Course No. 9SV109

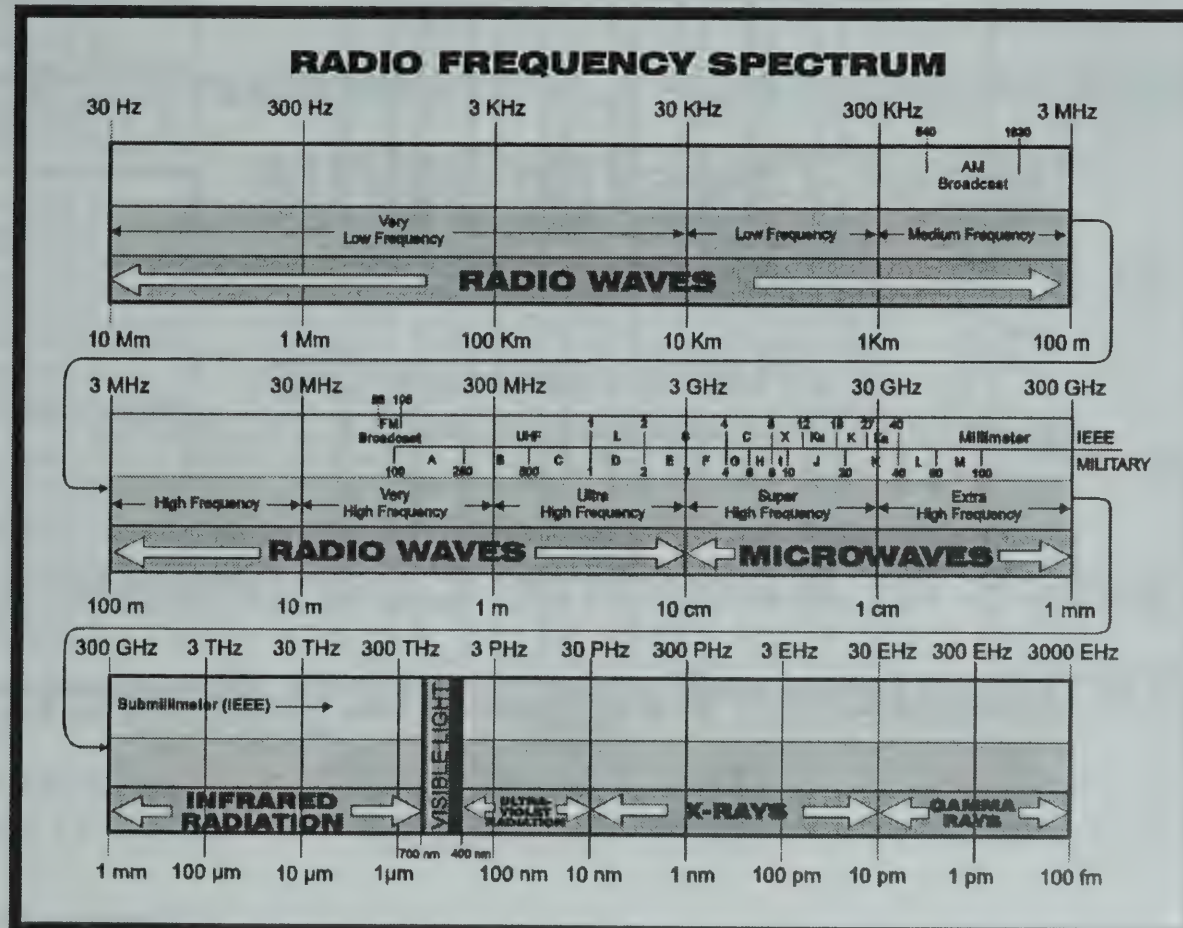
Reference 5c

Physics of Satellite Communications (RF Basics - Frequency Spectrum)

Physics of Satellite Communications

RF Basics

Frequency Spectrum



Commercial Satellite Communication Applications

Course No. 9SV109

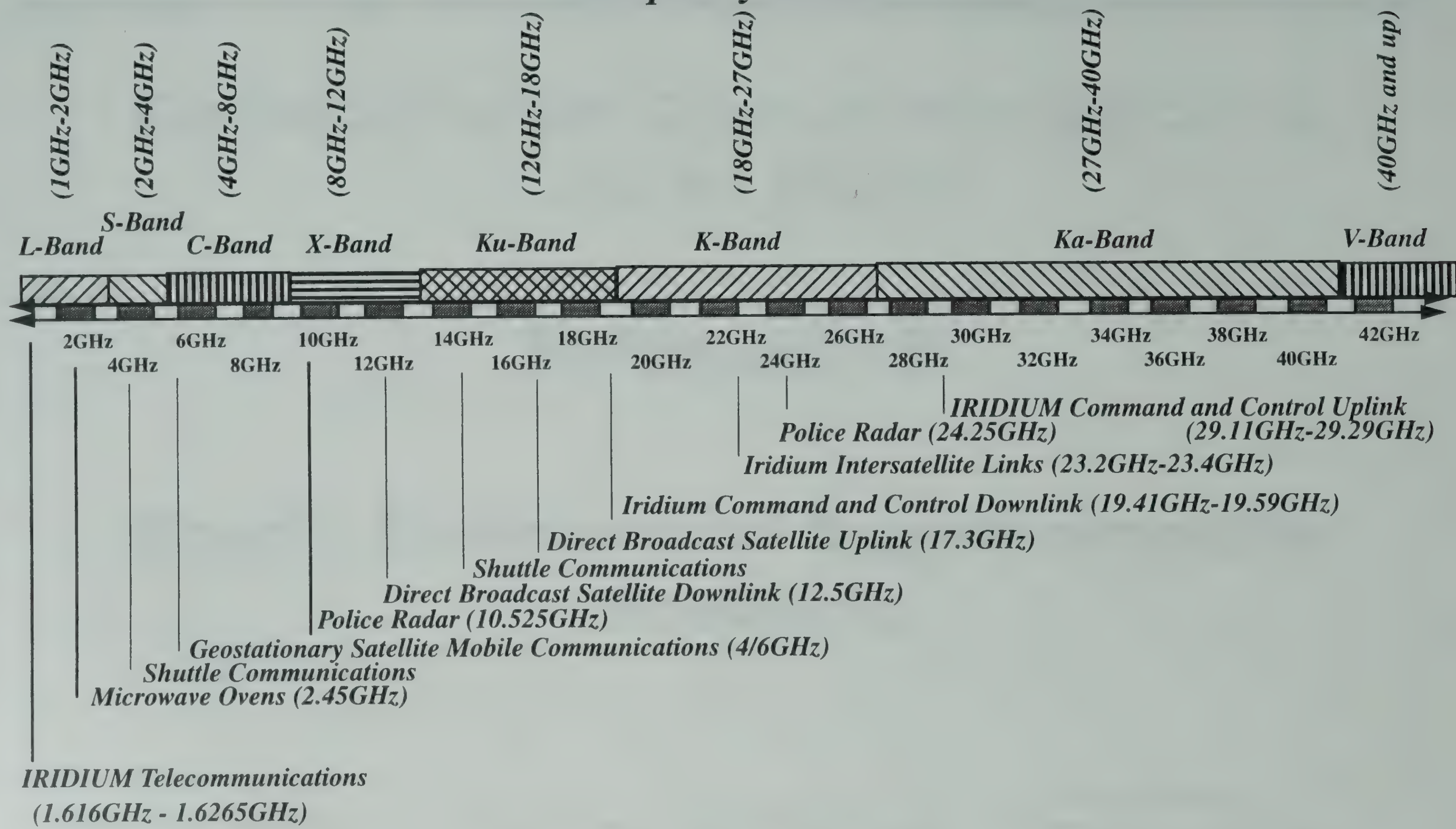
Reference 5d

Physics of Satellite Communications (RF Basics - Frequency Bands)

Physics of Satellite Communications

RF Basics

Frequency Bands

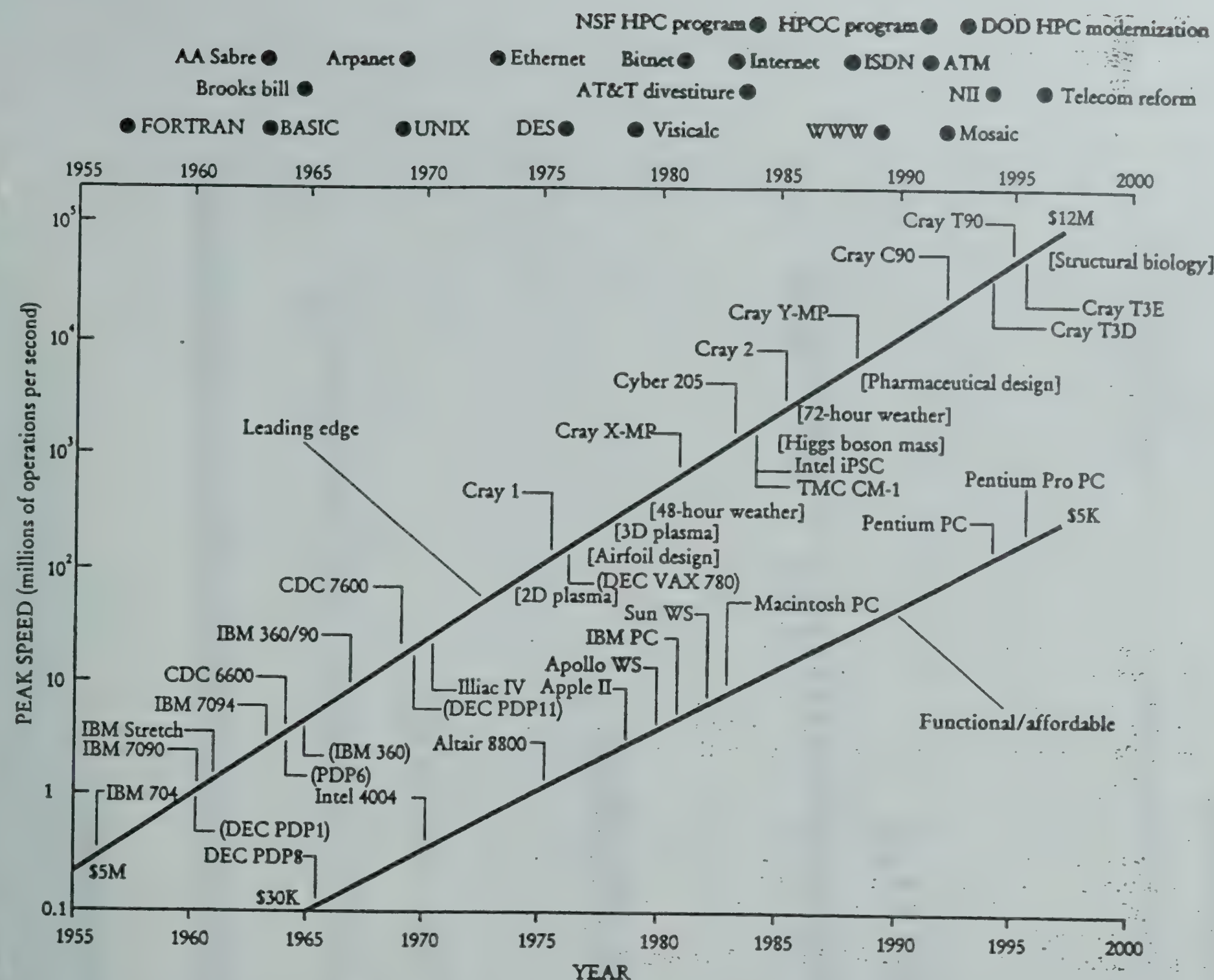


Commercial Satellite Communication Applications

Course No. 9SV109

Reference 6

Chart - Commercial Supercomputer Products



GROWTH OF COMPUTER TECHNOLOGY SINCE 1955, showing advances in average commercial computer performance and milestone events. Those milestones shown above the upper, or leading-edge, curve are commercial supercomputer products, and those below the curve are other important related events. Milestones in parentheses are not leading edge. Note that individual milestones do not necessarily fall on the curve, although they are depicted that way. The lower curve shows milestone dates of important processors at the affordable level, first for experiments (for example, the PDP8 in 1966) and later for desktop computers (for example the Pentium PC in 1994). Shown in brackets are computational problems that are solvable in reasonable times at the indicated level of computer performance. Approximate mid-level system prices are shown in dollars of the time. At the top of the figure are milestone dates, marked by dots, for events of related technology, software, legislation and so on. In almost all cases, dates and performance levels are approximate. FIGURE 1

strated that it was possible to build quite large computing machines containing thousands of vacuum tubes. Also, the architectural concept of the stored program had been introduced. But most important of all, in 1947, at AT&T's Bell Telephone Laboratories, John Bardeen, Walter Brattain and William Shockley had invented the transistor, which was to prove to be a critical event in the dawning of the information age.

Start of the modern computer era (1956–65)

In 1956, IBM's high-end product was the IBM 704 computer, whose design had evolved from that of the IBM 701. This computer had a ferrite core memory, which had recently been invented by Jay W. Forrester. Engineering Research Associates' Atlas II, installed at the National Security Agency in 1954, was the first computer to use a ferrite core memory. The IBM 704 memory stack contained 32 768 36-bit words and cost over $1 million—about $1 per bit. Magnetic drums served as a secondary storage system. Like most computing machines built up to that time, there was no operating system. There was, however, a symbolic assembler program (SAP), which made it possible to program the machine.

By that time, however, it had become clear that a language programming tool was required if these ever more powerful computers were to be used effectively. For the IBM 704 computer, IBM provided a higher-order-language formula translator program, FORTRAN, developed under the leadership of John W. Backus and a dozen collaborators. Similar efforts were ongoing elsewhere in the US and UK, but it was the delivery of a successful FORTRAN compiler along with a primitive operating system in 1957 that was another significant event in the maturation of the emerging computer industry. It was now possible for scientists to program their problems with relative ease.

In 1960, IBM replaced the IBM 704 and its successor, the IBM 709, with a solid-state version of the same architecture, the IBM 7090. The vacuum-tube–based electronic computer was now obsolete. Magnetic core re-

Commercial Satellite Communication Applications

Course No. 9SV109

Reference 7

Defense Department Constructs Global Communications Network

Defense Department Constructs Global Communications Network

Demand assigned multiple access technology equals private sector links for mobile battlefield commands.

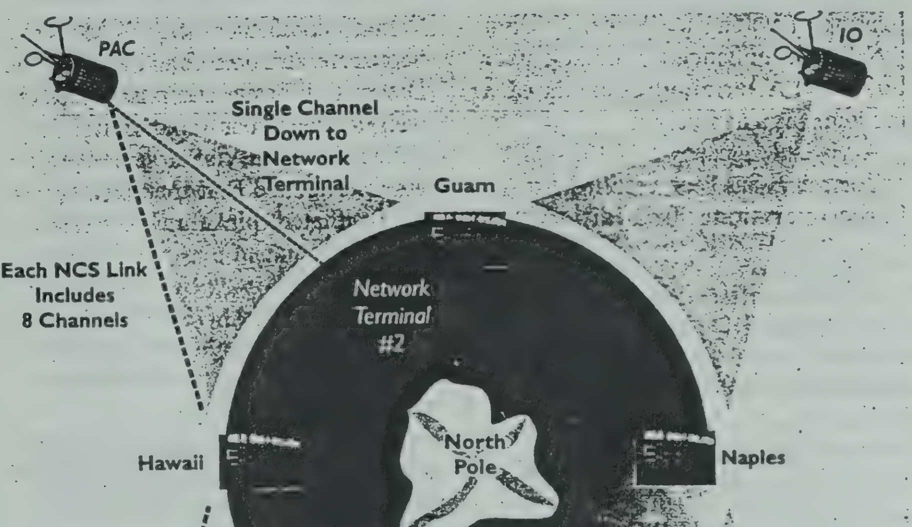
Military communications are moving from point-to-point links for tactical operations into the global network environment with worldwide satellite communications connections. In much the same manner as cellular telephone subscribers do, battlefield commanders using man-portable radios have near-real-time access through the application of demand assigned multiple access satellite communications.

More than 1,000 radio terminals operating with a demand assigned multiple access, or DAMA, capability already are fielded through a U.S. Army Communications-Electronics Command procurement program. Those already in place are mostly for Special Operations Forces, and some are for Army units. An additional 4,000 AN/PSC-5 radios—all from Raytheon Systems Company (formerly Hughes Defense Communications), Arlington, Virginia—are in production and are being delivered to tactical units. These radios also contain a DAMA technology modem from ViaSat, Carlsbad, California, for access to the U.S. Navy/Hughes Space and Communications Company ultra high frequency (UHF) satellite constellation (see page 71).

ViaSat and the U.S. Air Force have recently completed installation and achieved initial operational capability with four 5-kilohertz DAMA satellite communications network control stations. As the prime contractor to the Air Force Electronic Systems Center under an approximately $35 million contract for the network control stations, the company developed the 5-kilohertz technical capability for each network facility at four widely separated locations around the globe. The sites provide uplinks to the UHF satellite constellation.

Under a follow-on contract, ViaSat is already developing a software upgrade to add 25-kilohertz DAMA channel control, which is scheduled for implementation at each of the four network stations by the end of this year, according to Larry G. Taylor. He is ViaSat's director of UHF programs. In comparison with today's single-call-per-channel mode, the company's 5-kilohertz DAMA enables the military services to achieve more efficient use of expensive satellite resources by sharing single channels among numerous network terminals and subnetworks, Taylor explains.

The focal points for the 5-kilohertz DAMA network control stations are at four Navy installations: Guam; Norfolk, Virginia; Wahiawa, Hawaii; and Naples, Italy. Each of the network control station sites is in view of two UHF military satellites, one to the east and the other to the west, Taylor elaborates.



Four network control stations around the world coordinate ultra high frequency satellite communications via demand assigned multiple access (DAMA) channels. This technology links users within the footprints of four geosynchronous satellites into a global communications network.

This ring network architecture supports traffic between any two points in the world below 65 degrees latitude and gives each channel two potential routing paths.

During installation and worldwide testing of the fourth control station on Guam, voice and data traffic were successfully passed between ViaSat headquarters and the Guam site, initially using a short two-hop path going west through Hawaii, Taylor offers. Then, after a simulated failure of the Hawaii control station, he relates, the network automatically connected an alternative path going east via Norfolk and Naples. Full operational capability for DAMA network control stations is scheduled for 2000.

Commanders are allocating successively more 5-kilohertz satellite channels to DAMA operations, supporting the growing network terminal population the individual armed services are fielding, Taylor maintains. He reveals that several different 5-kilohertz DAMA terminals for the services have already received interoperability certification, including the Hughes/ViaSat AN/PSC-5 enhanced manpack user terminal. A terminal consists of a modem plus a transceiver.

A ViaSat/Magnavox MD-1324/ARC-187 terminal has been certified for Air Force operations. In addition, the Motorola/Titan LST-5D has been certified, and those of Rockwell, Cincinnati Electronics, E-Systems and others are in the process of certification testing or development. Some of these radio terminals for Navy and Air Force units incorporate DAMA modems from ViaSat's competitors such as Motorola, Scottsdale, Arizona; Titan Linkabit, San Diego, California; and possibly Rockwell Collins, Cedar Rapids, Iowa.

Lee Taylor, ViaSat's senior project engineer for the DAMA system, displays the ultra high frequency satellite communications constellation's coverage of the globe. The company's network control stations are located in Guam; Wahiawa, Hawaii; Norfolk, Virginia; and Naples, Italy. Each is within the footprint of two geostationary spacecraft.

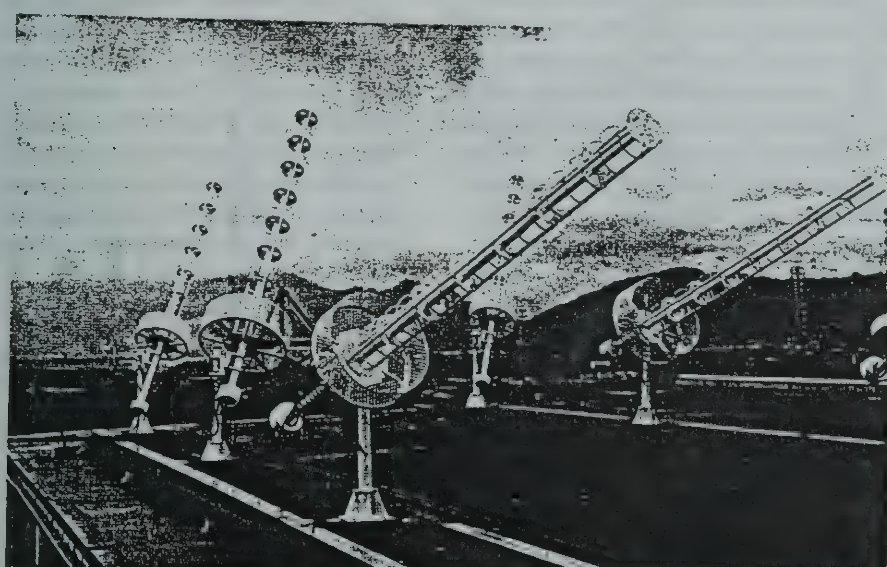
Lee Taylor, a ViaSat senior project engineer for the DAMA program, who is not related, picks up from his colleague Larry Taylor to confirm that, collectively, the four network stations provide the ability to handle—with a geographically separated alternate controller for every channel—up to eight 5-kilohertz DAMA channels for each satellite footprint of the entire worldwide UHF constellation. Military commanders can achieve dramatically more efficient use of satellite resources through the DAMA station technology, he declares.

There are two categories of gain: time division multiple access and DAMA gain. Time division multiple access gain results from multiplexing several lower rate services onto the channel, which can carry approximately 5,000 bits per second using the current waveform. Fully automated DAMA provides an additional sizable gain by dynamically connecting users to time slots only when they are actively communicating. This eliminates most of the wasted bandwidth that results from inactive users remaining on the channel, but not transmitting, Lee Taylor asserts. Transponders on any of the types of 5-kilohertz satellites can be operated in the DAMA mode, including on fleet satellites, LEASAT spacecraft and UHF follow-on payloads.

The 5-kilohertz DAMA technology offers three types of communications service: voice, data and message circuits. A circuit provides a continuously open pipe at a constant input/output rate and is most useful, Lee Taylor emphasizes, in situations where the duration of the communications need cannot be predicted.

When the length of data communications is precisely known, such as in the case of a computer-to-computer file transfer, the message can be divided into small packets and sent at a variable input/output rate per frame in the background relative to circuit services, Lee Taylor clarifies. Exactly enough packets are allocated to fill up each frame after all active circuit services have been accommodated. This feature allows highly efficient use of available channel capacity.

All three types of services are offered on a local satellite—one that is in direct view of the network control station. Voice circuits operate at 2.4 kilobits per second and data circuits at rates from 75 bits per second to 2.4 kilobits per second. Two-party traffic includes individual packet and final message acknowledgments to the orig-



An antenna array configuration for the current eight-channel network at each control-station site consists of two transmit and one receive antenna per side. This Hawaii station configuration includes all three west-side antennas, the east-side receive antenna, and in the foreground, an east-side transmit antenna. In situations with multiple closely spaced satellites, the network control-station antennas are typically pointed to access all spacecraft rather than being optimized for a particular satellite.

inator and is deemed reliable because the originator receives confirmation if the message is received. Subnetwork multipoint delivery message services are also provided, although without the acknowledgment feature.

Lee Taylor illustrates that, in the system's architectural approach, the 5-kilohertz DAMA is time division multiple access with centralized control. The primary functions of the network control station involve generation of the frame timing signal to which all network terminals synchronize and allocate channel resources. The vehicle for asserting these timing signals is a set of in-band order wires, he continues. Each time division multiple access channel has a single, forward order wire time slot carrying timing and control information from the controller to the network terminals.

A variable number of shared reverse order wire time slots carry control information—requests for communications services—from terminals back to the controller. Though the order wire traffic is designated sensitive, unclassified by the intelligence community, it is nonetheless encrypted, and each terminal's order wire encryption equipment must be endorsed for this application by the National Security Agency, Lee Taylor explains.

Larry Taylor points out that the ViaSat DAMA technology enables scheduling of satellite access on an as-needed basis so that users requiring a channel can make a request and immediately obtain the authority to use it. He contrasts this new capability with the previous method—operating on a single-channel-per-carrier basis—where a single telephone conversation occupies the channel's entire bandwidth. Even more cumbersome, he asserts, has been the access process that required users to request satellite access in writing. Written approval was also required for specific periods of time. Using this procedure meant that satellite access was assigned on a nondynamic basis even when requirements changed.

In contrast, "DAMA provides the ability to schedule satellite access on an as-needed basis. When a user requests access, it can be granted on a real-time or near-real-time basis, determined through a user's profile and precedence," Larry Taylor maintains. The Joint Chiefs of Staff have passed this access capability, provided by DAMA technology, down to the network control stations. The concept is based on assigning priority for each user in advance. Users are granted satellite access through dynamic assignment, he states.

"When a user requires a satellite channel, a request is initiated. If the channel is not already engaged by a user with a higher precedence, authority is granted for its use," Larry Taylor notes. "Through the application of DAMA technology, potential access to satellite channels is expanded more than 100 times, making user immediate access much more likely. This DAMA function resides within a computer at the four network control stations," he emphasizes.

Larry Taylor describes how eight UHF satellites are paired in four geostationary orbital positions so that a pair of spacecraft, separated by approximately 1 degree, is within range of at least one of the four ground station terminals. This arrangement provides double capacity for each of the control station locations. The site is selected so that an overlapping footprint exists for each of the spacecraft in the pair.

He characterizes ground station sites that are within the coverage area of two satellites as a backup communications advantage. One ground station can serve as a backup for another. "If one station goes off the air, another can provide a relay between satellite footprints. This capability also means that a user can request service to another user who is not located within the same satellite's footprint. This request is automatically relayed via the overlapping footprint arrangement—a new capability for the Defense Department," Larry Taylor stresses.

He continues that ViaSat is maintaining the four network control stations in its initial operational capability design with the 5-kilohertz DAMA channels. "Once the 25-kilohertz DAMA capability has been added later this year, each ground station will be fully compatible with all forms of DAMA. The next step will be to add more channels at each facility. Each station supports eight channels within a satellite's footprint, or a total of 16 channels.

"Additional channels will be added for each station under the auspices of

the Navy. Through incremental increases, eventually there will be up to 64 channels available within each satellite's footprint," Larry Taylor declares. "Within the next two years, the Air Force will turn control of the ground stations over to the Navy, as part of the Joint Chiefs of Staff's concept for the network's operation, he says.

Other centralized capabilities are also being added to the DAMA control stations through a separate Navy network management system. The location for the centralized management function is expected to be in the Washington, D.C., area. The center will control all of the network stations, proving a real-time basis for updating the database with users and their priority levels. Mainly a software function, the dynamic reassignment of priorities is to respond rapidly to changing world situations as they arise in specific geographic areas, Larry Taylor confirms.

"This database capability and network control can very rapidly handle reassignment of priorities and transmit the data, distributing it to all of the worldwide facilities. The whole concept is considered a monumental change in the way satellite communications have been operated," Larry Taylor observes.

"The AN/PSC-5 satellite radio terminals accomplish access to the satellite network control station, where access privileges from the control station are determined. The system also ascertains whether the user to whom the link is being requested is available. If that user is available, the connection automatically is completed," Larry Taylor reports.

Along similar lines, Lee Taylor points out that fully automated DAMA provides an additional sizable gain by dynamically connecting users to time slots only when they are actively communicating. This feature eliminates most of the wasted bandwidth that results from inactive users remaining on a channel without transmitting. Transponders on any type of 5-kilohertz satellite can be operated in the DAMA mode.

He continues that channel controllers for the 5-kilohertz system adapt to accommodate a variety of terminals and situations "and, in many cases, do so dynamically." Half-duplex—those which can both receive and transmit, but not simultaneously—are ordinarily limited to one service at a time when operating in nontime division multiple access systems. With 5-kilohertz DAMA technology, the terminals are provided sufficient space between time slots so that they can participate in multiple, simultaneous, independent services or in full-duplex mode. "This is an advantage of time division multiple access operation that offsets the incumbent frame-buffering delays," according to Lee Taylor.

Successively, commanders-in-chief are allocating more 5-kilohertz UHF satellite channels to DAMA operations. This approach coincides with the sizable number of network terminals in the production pipeline and the population already being fielded. By the end of the year, the armed forces will enter the fully automated DAMA satellite communications era. With 5- and 25-kilohertz DAMA capability, this global communications system will provide a path to meet tactical user needs regardless of their locations. *—CAR*

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Commercial Satellite Communication Applications

Course No. 9SV109

Reference 8

Symbols and Acronyms

a	Semi-major axis (major axis = 2a)
A	Some times used to indicate an amplifier
A	Altitude
A	Aperture
A	Slant distance (also see S)
ACK	Acknowledge a good transmission (also see NAK)
A_e	Effective aperture
AM	Amplitude Modulation
AMP	Amplifier
apfd	Aggregate power flux density
ARQ	Automatic Repeat reQuest
ASIC	Application Specific Integrated Circuit
A_z	azimuth distance P3-17
b	bite (lower case abbreviation) = 1/8 Byte
b	Semi-minor axis (minor axis = 2b)
B	Byte note (upper case abbreviation) = 8 bits = 8b = Octet
Beam width	usually given at the HPBW
BPSK	Binary Phase Shift Key
BSS	Broadcast Satellite Service
BW	Bandwidth
c	distance between the foci of an ellipse
C	Carrier
C/IM	Carrier to intermodulation distortion ratio P 2C-8
C/N	carrier to noise ratio
CDMA	Code Division Multiple Access
CNR	carrier to noise ratio

List of Symbols and Acronyms

CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CTE	Coefficient of Thermal Expansion
d	diameter (e.g., for a circular aperture)
D_0	"Dee Sub Zero" or "D Zero" = Directivity
dB	one tenth of a Bell, (note small d big B)
DBS	Direct Broadcast Satellite
DoD	Department of Defense
DSN	Deep Space Network
DTH	direct to Home
e	Eccentricity
E_b/N_0	Energy per bit to noise ratio
E1	European version of T1 2.048 Mbps (also see T1)
EBU	European Broadcast Union
e_c	Conducted efficiency
e_d	dielectric efficiency
EES	Earth Exploration Satellite band
EIA	Electronic industry Association
EIRP	Effective Isotropically Radiated Power
EIRP	Equivalent Isotropically Radiated Power
epfd	equivalent power flux density
ERO	European Radiocommunication office
ETSI	European Telecommunication Standard Office
FCC	Federal Communications Commission
FDMA	Frequency division multiple access
FEC	Forward Error Correction
FM	Frequency Modulation
FSK	Frequency Shift Key
FSS	Fixed Satellite Service

List of Symbols and Acronyms

FTC	Fiber to the Curb
G	Gain
GEO	Geostationary earth orbit = Geo synchronous earth obit with 0 deg. eccentricity
G_p	Free space path loss
G_r	Receive antenna gain
HEO	highly elliptical orbit
HPBWB	half-power beam width, (i.e., width of the beam at –3dBic or –3 dB relative to the isotropic center of the beam
i	inclination
I	interference
IC	Integrated Circuit
IEC	International Elecrotechnical Commission
IF	Intermediate Frequency
IP	Internet Protocol
ISA	Industry Standard Architecture a 16 bit, nominally 8 MHz computer bus being replaced by PCI
ISO	International Standards Organization
ITU	International Telecommunications Union
JPEG	Joint Picture Expert Group
k	metric prefix for 1000
k	Boltzmann's constant = 1.38 e-23 J/K
k	number of input bits
K	Kelvin (formerly ^oK)
K	code constraint length
k/n	code rate (i.e., input bits to output bits ratio)
kb/s	1000 bits per second
LEO	Low Earth Orbit
LHP	left hand polarization
LIM	Limiter

List of Symbols and Acronyms

LNA	Low Noise Amplifier
M	Mean Anomaly
MEO	Medium Earth Obit
MMH	Mono-Methyl Hydrazine
MPEG	Motion Picture Expert Group
n	number of output bits for a code
N_β	Noise power
NAK	Not ACK (or not acknowledge a good transmission)
NGSO	Non-Geostationary-Orbit
nmi	nautical mile
N_o	Noise power density
NPR	Noise to Power Ration
NTIA	National Telecommunications and Information Administration
Octet	alternate way to say Byte
OSI	Open System Interconnection model defined by the ISO
P_b	Probability of a bit error
PCI	Peripheral Component Interface, a 32 bit 33 MHz computer bus
PCM	Pulse Code modulation
PFD	Power Flux Density
PM	Phase Modulation, Pulse modulation ??
POTS	plain old (analog) telephone system
pps	Packets per second
P_r	Power received
PRBC	Pseudo Random Binary Code
PRN	Pseudo Random Number
PSK	Phase Shift Key
PWR	Power
QAM	Quadrature Amplitude Modulation

List of Symbols and Acronyms

QPSK	Quadrature Phase Shift key
r	Axial ratio, a measure of the ellipticity of polarization = major axiis / minor axis
R_1	Axial ration of the transmit antenna
R_2	Axial ration of the receive antenna
RAAN	Right ascension of the ascending node
RAAN	right ascension of the ascending node
R_b	data rate in Hz
RF	Radio Frequency
RHP	Right hand polarization
S	Distance
S	Slant Distance (also see A)
SATCOM	Satellite Communications
SCPC	Single Channel Per Carrier
SETI	Search for Extraterrestrial Intelligence
SGLS	Space-Ground-Link-System
Sidereal day	360° Rotation of the earth = 23 hours 56 minutes 4 seconds
SNR	Signal to noise Ratio
SPADE	Single channel-per-carrier PCM multiple-access demand assignment equipment
SREJ	Selective rejection Aloha
SSB	Single Side Band
SSPA	Solid state power amplifier
T	Temperature
T&C	Telemetry and Control 2C-9
T1	phone line standard = 1.544 Mbps (also see E1)
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TIA	Telecommunication Industry Association
TT&C	Telemetry Tracking and Control

List of Symbols and Acronyms

TWT	Traveling Wave Tube
TWTA	Traveling Wave Tube Amplifier (also see SSPA)
VSAT	Very Small Aperture Terminal
W	Watt
W	Bandwidth (also see BW)
β	Modulation index (e.g., used in FM)
γ	Transmission gain of a specific satellite link subject to interference evaluated from the output of the receiving antenna fo the satellite to that output of the receiving antenna of the earth station P4-17
η	Aperture efficiency
λ	Wavelength
π	$\cong 3.14159$
θ	angle
Ω	Right ascension of the ascending node
ω	Argument of perigee

a	Semi-major axis (major axis = 2a)
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